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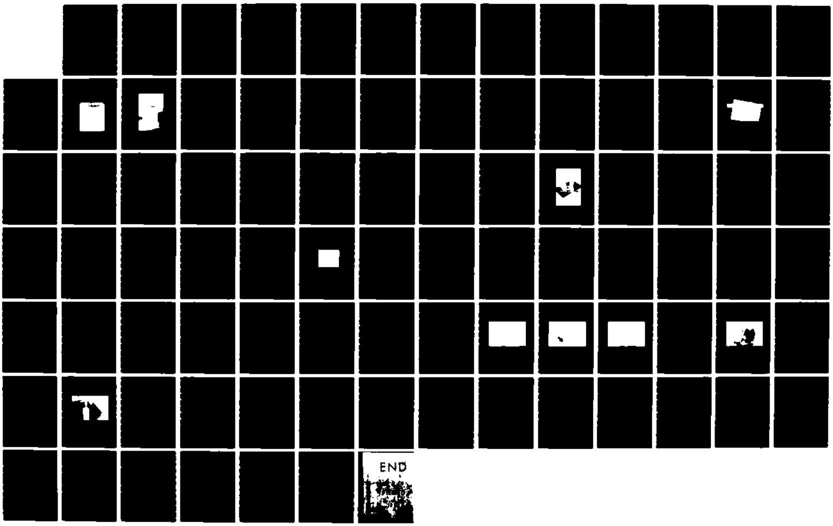

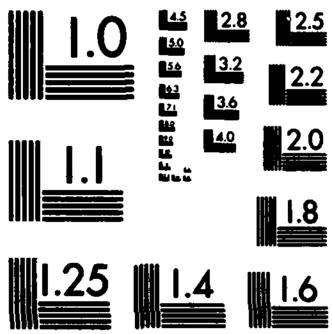

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Final Report
for the period
September 1980 to
April 1982

Capacitor Hardness Demonstration Program Final Report

August 1983

Authors:
A. Ramus
W. White

Maxwell Laboratories, Inc.
8835 Balboa Avenue
San Diego, CA 92123

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Air Force Space Technology Center
Space Division, Air Force Systems Command
Edwards Air Force Base,
California 93523

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FOREWARD

This final report was prepared by Maxwell Laboratories, INC and was sponsored by the Air Force Rocket Propulsion Laboratory under Contract F04611-80-C-0048, Job Order No. 305812PM. The program was monitored first by Capt Michael R. Brasher and later by 1Lt Philip D. Roberts.

Work on this contract began in September 1980 and was completed in April 1982, and the pertinent studies of this period are reported herein. This report was submitted by the authors in February 1982.

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Project Manager

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Chief, Satellite Propulsion Branch

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MELVIN V. ROGERS
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FOR THE DIRECTOR

CLARK W. HAWK
Chief, Liquid Rocket Division

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This final report describes discharge-life tests on capacitors which use polyvinylidene fluoride (PVDF) as the principal dielectric. Discharge-life tests on all-film capacitors impregnated with silicone oil and recent tests on PVDF/paper capacitors impregnated with castor oil are described. The manufacturing procedure of vacuum-qualified PVDF/paper/castor oil capacitors is discussed.

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CONVERSION FACTORS FOR U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

To Convert From	To	Multiply By
angstrom	Meters (m)	1.000 000 x E -10
atmosphere (normal)	Kilo pascal (kPa)	1.013 25 X E +2
bar	kilo pascal (kPa)	1.000 000 X E +2
barn	meter^2 (m^2)	1.000 000 X E -28
British thermal unit (thermochemical)	joule (J)	1.054 350 X E +3
cal (thermochemical)/cm^2	meta joule/m^2 (MJ/m^2)	4.184 000 X E -2
calorie (thermochemical)	joule (J)	4.184 000
calorie (thermochemical)/g	joule per kilogram (J/kg)*	4.184 000 X E +3
curies	giga becquerel (Gbq)†	3.700 000 X E +1
degree Celsius	degree kelvin (K)	$t_K = t°_C + 273.15$
degree (angle)	radian (rad)	1.745 329 X E -2
degree Farenheit	degree kelvin (K)	$t_K = (t°_F + 459.67)/1.8$
electron volt	joule (J)	1.602 19 X E -19
erg	joule (J)	1.000 000 X E -7
erg/second	watt (W)	1.000 000 X E -7
foot	meter (m)	3.048 000 X E -1
foot-pound-force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E -3
inch	meter (m)	2.540 000 X E -2
jerk	joule (J)	1.000 000 X E +9
joule kilogram (J/kg) (radiation dose absorbed)	gray (Gy)*	1.000 000
kilotons	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E +3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E +3
ktap	newton-second/m^2 (N-s/m^2)	1.000 000 X E +2
micron	meter (m)	1.000 000 X E -6
mil	meter (m)	2.540 000 X E -5
mile (international)	meter (m)	1.609 344 X E +3
ounce	kilogram (kg)	2.834 952 X E -2
pound-force (lbf avoirdupois)	newton (N)	4.448 222
pound-force inch	newton-meter (N·m)	1.129 848 X E -1
pound-force/inch	newton/meter (N/m)	1.751 268 X E +2
pound-force/foot^2	kilo pascal (kPa)	4.788 026 X E -2
pound-force/inch^2 (psi)	kilo pascal (kPa)	6.894 757
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E -1
pound-mass-foot^2 (moment of inertia)	kilogram-meter^2 (kg·m^2)	4.214 011 X E -2
pound-mass/foot^3	kilogram-meter^3 (kg/m^3)	1.061 846 X E +1
rad (radiation dose absorbed)§	gray (Gy)*	1.000 000 X E -2
roentgen§	coulomb/kilogram (C/kg)	2.579 760 X E -4
shake	second (s)	1.000 000 X E -8
slug	kilogram (kg)	1.459 390 X E -1
torr (mm Hg, 0° C)	kilo pascal (kPa)	1.333 22 X E -1

*The gray (Gy) is the accepted SI unit equivalent to the energy imparted by ionizing radiation to a mass and corresponds to one joule/kilogram.

†The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

SECTION 1

INTRODUCTION

Maxwell Laboratories is pleased to present this Final Report on the Capacitor Hardness Demonstration Program to the Air Force Rocket Propulsion Laboratory (AFRPL), Edwards Air Force Base. This report describes the results of a program to develop a 2.2 kV capacitor storing 190 J with the energy density of 88 J/Kg (40 J/lb), to be used in the fast discharge circuit of a Teflon Pulsed Plasma Thruster. Capacitor specifications are shown in Table 1-1.

Maxwell conducted a previous development program for an all-film radiation resistant capacitor to be used by AFRPL in a thruster designed to perform station keeping for a satellite in geosynchronous orbit[1]. This program resulted in the development of a prototype all-film capacitor using polyvinylidene fluoride (PVDF) manufactured by the Kureha Corporation. This is a capacitor film for which there is only limited data.[2] This capacitor consisted primarily of a PVDF film and aluminum foil winding impregnated with silicone oil. This development program was followed by the current Hardness Demonstration Program which is the subject of this Final Report. The objective of this current program was the evaluation of the vulnerability of the PVDF all-film capacitor to specified levels of ionizing radiation.

During the current program, new life data on the all-film, PVDF capacitors caused the basic program objectives to be changed from hardness demonstration to one of construction and evaluation of long-lived paper/PVDF capacitors impregnated with castor oil. These capacitors would be capable of meeting all requirements with the exception of that on radiation resistance. The background of this redirection is summarized in the following paragraphs.

The PVDF all-film, silicone oil impregnated capacitor developed previously, initially showed promise in meeting all

TABLE 1-1
CAPACITOR SPECIFICATION AND GOALS

SPECIFICATION	GOALS
Energy	190 J
Voltage	2.2 kV
Voltage reversal	25 Percent
Capacitance	80 μF, +10% -5%
Inductance	15 nH
Loss factor @ 25°C, 120 Hz	0.010, Goal 0.013, Maximum
Peak current	30 kA
Initial dI/dt	10^{10} A/s
Pulse rate	0.17 Hz (normal) 1.00 Hz (maximum)
Burst duration	Indefinite
Capacitor temperature range	-20°C to +50°C (design) -35°C to +70°C (goal)
Ambient pressure	10^{-4} Torr
Radiation environment	See Section 1.
Life	>10^7 shots
Reliability	Not specified
Gross energy density	88 J/kg (40 J/lb) @ 2.2 kV
Weight	4.75 lbs
Shape	Cylindrical
Dimensions	10.5 cm (4.125 in.) ID 18.4 cm (7.25 in.) length

requirements. This was indicated by discharge-life tests conducted at higher-than-rated voltage. These accelerated tests resulted in extrapolations leading to the conclusion that capacitor life at the rated voltage of 2.2 kV would exceed 10^7 discharges. In addition to long life, this capacitor was expected to have resistance to damage by ionizing radiation because all constituents were known to be resistant to radiation damage. Paper, a common constituent in long-lived capacitors, was deliberately excluded because it was known to undergo thermal peaks and gas liberation when irradiated, which would limit its life.

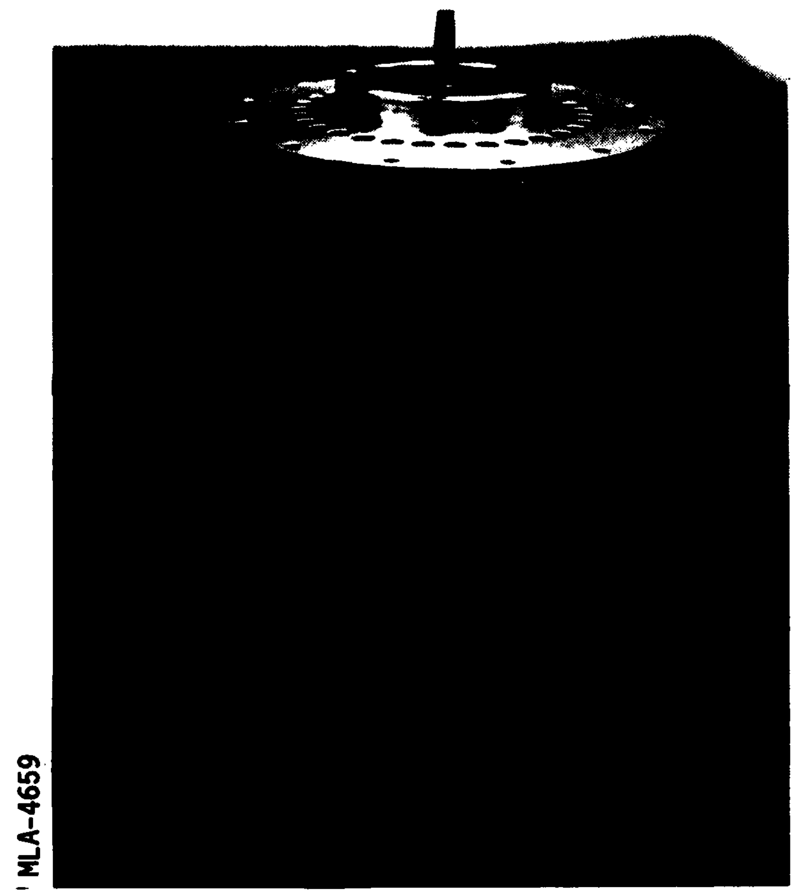
To evaluate discharge life within the time constraints of the previous program, these accelerated tests at higher-than-rated voltage were mandatory. The charge voltage of 3.9 kV and discharge current of 53 kA was used rather than the rated values (Table 1-1). Extrapolations, to be described in this report, were then necessary. They indicated that the life at 2.2 kV would meet or exceed the 10^7 shot requirement; therefore, the current program to test the radiation vulnerability was the next step in the capacitor development.

During the current program, discharge-life test results from Maxwell, Fairchild, and AFRPL, which were conducted at the 2.2 kV rated voltage, clearly showed the life of these all-film capacitors fell short of the requirements. Therefore, radiation hardness tests of the all-film capacitors were indefinitely postponed and attention was focused on alternative capacitor designs capable of long life. The overall program goals of the thruster allowed a compromise to be made on radiation resistance, in order to obtain a long lived capacitor which could meet schedule requirements for AFRPL thruster experiments. Maxwell already had a background of successfully manufacturing K-F film/paper/castor oil capacitors previously for AFRPL-sponsored thruster tests (at Fairchild) which were in the $>10^6$ shot range. With added improvements in winding technology which occurred since those tests, we concluded that the K-F film/paper/castor oil capacitors should be

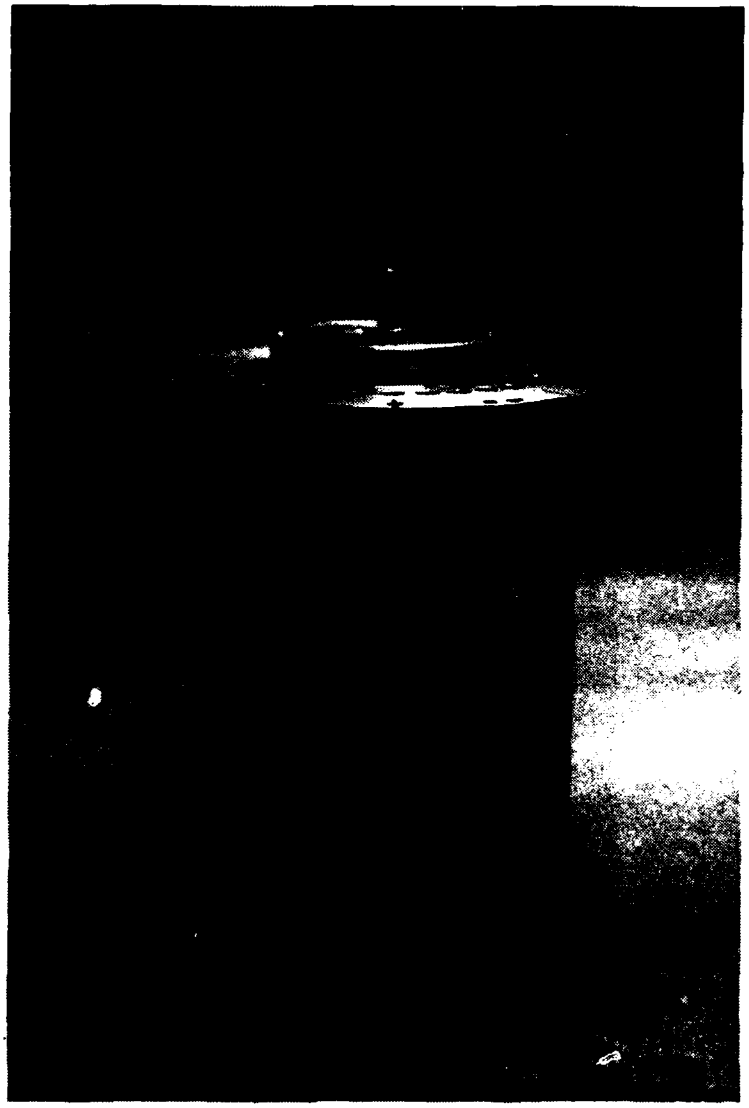
used for the present AFRPL requirement although these capacitors were not believed to be radiation resistant. Therefore, Maxwell proceeded with the manufacture of PVDF/paper/castor oil capacitors.

To ensure a defect-free product, we constructed a special air filtered winding room which included monitoring equipment to measure the concentration of airborne dust. All capacitors for AFRPL were wound under the strictest quality control. Furthermore, to meet the requirement on temperature range (-20°C to +50°C), we included special temperature compensation bellows to be discussed in this report. Figure 1-1 shows a capacitor manufactured during this program.

In keeping with the requirements of the modified program, two groups of PVDF/paper/castor oil capacitors were manufactured. In the first group, eight capacitors were constructed for accelerated testing at Maxwell and AFRPL. These tests were successful and showed, by extrapolation to rated voltage, that the capacitors can meet the life requirements with high confidence. A second group of capacitors was therefore constructed in special stainless cans capable of sustaining vacuum operation; and, at this writing, this group is being prepared for thruster tests at rated voltage. Figure 1-2 shows a capacitor ready for tests in the AFRPL thruster built by Fairchild. This capacitor is equipped with special flanges to fit the thruster and is painted black to enhance radiation cooling.



1-1. **Vacuum-qualified capacitor manufactured during this program.**



1-2. Vacuum-qualified capacitor equipped with special flanges and painted black to enhance radiation cooling.

SECTION 2

BACKGROUND

2-1 ALL-FILM CAPACITOR TEST RESULTS

In this section, we summarize the data on the all-film, silicone oil impregnated, PVDF capacitors and discuss its impact on the present Hardness Demonstration Program.

The discharge-life data on the all-film capacitors which were constructed during the previous technology program[1] are shown in Table 2-1. This discharge-life data was obtained by Maxwell and by Fairchild at the accelerated voltage of 3.9 kV. Extrapolations to predict life L at 2.2 kV were based on the equation:

$$L = kV^{-a} \quad ,$$

where

V = Charge voltage

k = Constant of proportionality

a = An empirical number, assumed constant (see text).

Experience has shown a to be constant for a particular capacitor configuration, dielectric system, and failure mode. We based our extrapolations on that basis. As shown, the mean time between failure (life at 37 percent reliability[3], also called the characteristic life) is 2.4×10^7 discharges and for 99 percent reliability, it is 1.4×10^7. Therefore, with capacitors made with appropriate winding tension, the life requirements appeared to be attainable (Table 1-1). This extrapolation is based on the assumption that a is constant throughout the range between the rated and the tested voltage. Although true for many types of capacitors, the recent evidence clearly showed this assumption to

TABLE 2-1

SUMMARY OF DISCHARGE LIVES OF 80 μF K-F POLYMER CAPACITORS

CAPACITOR COMPOSITION	Life From Data		Exponents		Extrapolations of Life	
	L (37%) @ 3.9 kV	L (99%) @ 3.9 kV	a (37%)	a (99%)	L (37%) @ 2.2 kV	L (99%) @ 2.2 kV
SILICONE OIL IMPREGNANT TEST AT MAXWELL (3.9 kV)						
Room temperature normal tension	2005	1600	15.4	14.9	1.4×10^7	0.8×10^7
Room temperature low tension	6010	4060	17.6	16.8	1.4×10^8	6.2×10^7
High temperature low tension (3.9 kV)	1007	595	17.6*	16.8*	2.4×10^7	1.4×10^7
Low temperature low tension (3.9 kV)	>9000	--	17.6	--	2.1×10^8	----
SILICONE OIL IMPREGNANT VACUUM (FAIRCHILD)						
Room temperature (3.9 kV)	4800	360	17.1**	11.9**	8.5×10^7	3.3×10^5
MIPB IMPREGNANT TEST AT MAXWELL ROOM TEMPERATURE						
3.9 kV test	2500	360	15.0***	11.3***	1.3×10^7	2.3×10^5
3.7 kV test	3900	470	14.4	10.7	0.7×10^7	1.2×10^5

* Slopes at high and low temperature were assumed equal to that of room temperature.
** Mean high-pot failure at 6.40 kV is taken for Fairchild capacitors (based on Maxwell data)
***Mean high-pot failure for MIPB impregnated capacitor is 6.57 kV

be incorrect for these PVDF all-film capacitors. Subsections 2-1 and 2-5 of this report discuss the basis for this assumption. During the current program, data appeared which showed that life was smaller than previously expected. For example, Maxwell tested two capacitors at 2.2 kV. In these two tests, life was 32,886 (test date 7/13/81) and 87,764 (test date 8/19/81), rather than the expected 10^7 discharges. At Edwards AFB, these results were confirmed in a test fixture which simulated the appropriate charge and discharge waveforms in a manner similar to that used at Maxwell. Also, actual thruster tests in vacuum at Fairchild showed capacitor life in the same range.

Autopsies[4] on failed capacitors did not indicate that a manufacturing error had occurred. Rather, body failures were prevalent as if a dielectric material defect or a foreign particle was included in the winding. Also, the high stress in the impregnant of a capacitor containing K-F polymer can, in principle, cause arcing within the impregnant between the foil and film. This is caused by the high dielectric constant of the PVDF compared to that of the impregnant; the field in the fluid equals that in the PVDF times the ratio k (PVDF)/ k (impregnant) or 10/2.7 = 3.7. Such arcing could result in capacitor life versus voltage which does not obey the exponential law above. Most of the background data which supports this exponential dependence applies to so-called "end-of-life" edge failures. In those cases, edge failures occur after significant edge wear becomes manifest by carbonization and erosion. This mechanism was not observed in the all-film, PVDF capacitors.

2-2 TECHNICAL PROGRAM REVIEWS

2-2.1 Meeting at Maxwell of April 28, 1981

As a result of these early failures, a meeting was convened at Maxwell consisting of capacitor experts from major laboratories throughout the United States. The objective of this

meeting was to assess the causes of the relatively short capacitor life and to recommend improvements in design to extend this life. Following are lists of the main recommendations drawn from that meeting.

a. Screening

1) Analyze unused dielectric oil at Jet Propulsion Laboratory (JPL) for water content. Analyze again after Maxwell processing.

2) Using crossed polarizers, analyze samples from rolls of dielectric film. Check for imperfections, such as scratches and high molecular weight gels. The film presently coming from Kureha is of poor quality compared to earlier material. Samples can also be taken after each capacitor is wound.

3) Analyze gases and other products produced during capacitor operation to determine chemical reactions taking place.

4) Use partial discharge analyzer (or dc corona detector, similar to the one now in operation at Los Alamos) to compare corona in an unused capacitor with that in a used capacitor.

5) Apply a dc voltage to 80 percent of rated voltage, in order to electrically condition the capacitor. This will help ensure complete impregnation.

b. Improve Materials

1) Reduce water content of dielectric fluid to the minimum possible. This may cause Maxwell to change outgassing procedures and use lower impregnant temperature, higher vacuum, and longer duration (days).

2) Use 20 centistoke rather than 5 centistoke silicone oil.

3) Use stabilized silicone oil. Dow Corning DC 560 series is a possibility. Stabilized oils are less likely to be affected by electric fields, temperature, or pressure.

4) Wind capacitors in a class 1000 clean room.

5) Consider replacing silicone oil with MIPB, or castor oil. They are not catalysts for the production of HF gas, as in contrast with silicone oil. Also, consider Fluorinert, an electronic liquid FC-40 produced by 3M Company, now under investigation at Sandia for use in capacitors. (Maxwell note: MIPB was used in an all-film PVDF capacitor, with results judged to be less favorable than those obtained with silicone oil.)

c. Improved Impregnation

1) Construct looser windings for better cooling and larger space factor. This would require major modification to Maxwell's Hilton machine. Sandia

would supply the drawings and other information needed to make the modifications.

2) Impregnate under pressure, at least 50 psi.

3) Use internal bellows.

4) Have some indication of when impregnation is complete. Either observe bellows movement, or change in capacitance on a high resolution capacitance bridge.

5) Wind foil and film with rough to smooth sides adjacent.

6) Use Kraft tissue between films.

7) Reflood capacitors during impregnation cycle. A possible procedure would be: impregnate, apply DCV (for outgassing), empty oil from can, impregnate again, etc.

d. Improved Can

There may be a need for silver metalization on the contacts of the Ceramaseal bushing. Only then can the bushing be assured of surviving the 900°C brazing temperature.

e. Other Considerations

1) Investigate influence of pulsed plasma power converter output frequency on film dielectric losses. Sixty-four KHz appears to be worst possible operating point for capacitor charging.

2) Investigate dc life of capacitors more thoroughly.

This meeting was followed by a capacitor autopsy performed on a failed all-film capacitor. Dr. Elizabeth Yen, a polymer chemist present at the capacitor autopsy, commented on the adhesion of the film to the foil. She suggested that polymerization had occurred. Polymerization can cause new mechanical and electrical conditions within the capacitor which could lead to premature failure.

2-2.2 Meeting at Edwards AFB, July 28, 1981

The steps to be taken to improve capacitor design in the short term were determined during a subsequent meeting at AFRPL, Edwards AFB. In summary, the plan which resulted from this meeting was the following:

a. Summary

1) Maxwell will formulate a materials test plan to grade the quality of the PVDF film obtained from Kureha. AFRPL will be apprised of this qualification procedure.

2. AFRPL will issue a change order to redirect the program. This order will include:

- The qualification procedure above
- The requirement to manufacture minimum of eight PVDF film, castor oil/paper capacitors in conventional steel cans for capacitor tests at AFRPL and Maxwell.

- The requirement for manufacture of minimum of twelve vacuum qualified K-F film/castor oil/ paper capacitors for thruster life tests at Edwards and Fairchild. These capacitors will include bellows assemblies.

- Capacitor failure mechanisms and material quality problems will be investigated within the limitations of program funding and schedule.

At this point, all work related to radiation hardness was suspended and the emphasis was on the manufacture and test of PVDF/paper/castor oil capacitors. The new plan was as follows:

b. <u>New Program Requirements</u>

1) Formulate a test plan to qualify materials in order to significantly increase the likelihood of constructing successful capacitors.

2) Construct eight K-F film/castor oil/paper capacitors in conventional steel cans for tests at AFRPL and at Maxwell.

3) Construct twelve PVDF film/castor oil/paper capacitors in vacuum qualified stainless steel cases for delivery to AFRPL for evaluation in their test facilities.

2-3 Material Qualification

In keeping with the new goals, Maxwell proceeded to improve investigating methods of winding quality. An important objective was the establishment of more detailed and complete qualification procedures on the capacitor constituents. One

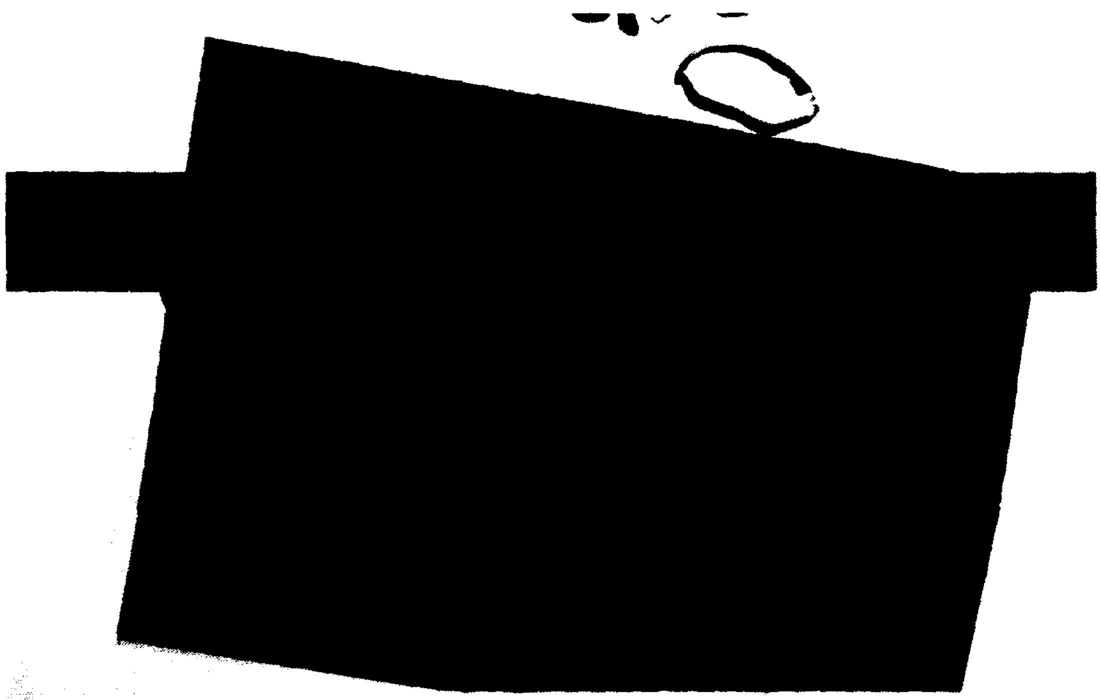
qualification method was recommended by Pennwalt, Inc., a manufacturer of films and an attendee of the April 28 meeting. They recommended a study of the light transmission properties of the PVDF film. In this method, polarized light is passed through the film and observed through another polarizer. Irregularities, such as stripes and localized nonuniformities along the length of the K-F film, can be observed. Of particular interest was the occurrence of "gels" within the film. These are small, oval-shaped dark regions roughly 1/8 in. in length and 1/16 in. in width, as shown in Figure 2-1. We examined the first few turns of several different rolls of PVDF film. The density of gels was observed to vary from ~1 gel per ft^2 to ~5 gels per ft^2 of film.

a. Use of Polarized Light. The main question was whether or not the gel was a region of reduced breakdown strength. We measured the breakdown strength in two different ways.

In one, we simply applied dc voltage to the rate of ~1 kV/s over an area of 1.2 $in.^2$ to a single thickness of PVDF film between two metal electrodes. The stressed area included the gel which was marked by a circle made with a felt tip pen.

For the air samples, the breakdown occurred at ~6 kV, (in 12 micron thick film) in regions outside the circle. Out of 20 tests, two breakdowns occurred within the circle suggesting the gel broke down. However, these two breakdowns were not in the lower range of the breakdown voltage. Based on these experiments, we were not able to conclude that the gel was electrically weaker (due to stress) than the other areas of the film.

We then tested the film using 60 Hz ac. We placed a few square inches of the film in a shallow container containing silicone oil. (Without the silicone oil, the ac voltage produced intense corona which burned the film.) Then we applied 2 kV rms ac to the film using the same electrodes as above. In these cases, we never observed a breakdown through the gel.



MLA-4585

2-1. Section of PVDF film illuminated with polarized light. Photo is taken through a second Polaroid filter.

We also used doubled film thickness. The films were arranged so that a gel was located over a section of film without gels. In this way, if the gel had a dielectric constant which differed widely from that of the normal film, field enhancement would tend to break the film. Here too, the films never broke at the location of the gel. Therefore, we were unable to demonstrate that the gels constituted a region of reduced breakdown strength.

b. Sample Breakdown Voltage. With the continued objective of establishing qualification procedures, we studied the breakdown strength of single thickness K-F film in air. One such experiment was conducted with a cylindrical stainless steel electrode 6.4 cm dia x 6.9 cm axial length weighing 1.7 kg (3.7 lbs). (This corresponds to a pressure on the film of 0.76 psi.) The variation in breakdown strength was remarkably large; at times we could apply only 100 V or 200 V to the film. In other locations, we could charge to over 4 kV.

We first suspected that this variability in breakdown voltage of single films was caused by pinholes and defects. We then repeated this experiment with light-weight electrodes and did not reproduce this large variability. We now conclude that the film breakdown strength depended on pressure points and irregularities on the 1.7 kg electrode. Alternatively, fine airborne dirt on the order of 1-10 micron in diameter is also suspected of contributing to this variable breakdown strength.

These considerations stimulated further investigation into the filtered air environment in which we wind capacitors. Maxwell has always wound its capacitors in an environment which includes filtered and humidified air. Also, antistatic devices are installed in all winding equipment. The techniques which we employ are satisfactory for common films, but may not have been adequate for all-film PVDF capacitors. We concluded that more control of particle contamination should be a requirement for films with high dielectric constant.

We have considered possible causes for this sensitivity of films with high dielectric constant to dirt. For example, the mechanical pressure between films (in given voltage and film thickness) is directly proportional on the dielectric constant. For $k = 10$, $V = 2.2$ kV , and $d = 24$ micron, this pressure is 56 psi., as shown in the following calculation.

The electrostatic pressure P is given by the equation

$$P = (1/2)ke_oE^2$$

where

$$e_o = \text{Dielectric constant of free space}$$

$$= 8.9 \times 10^{-12} \text{ F/m}$$

$$k = \text{relative dielectric constant}$$

$$(\text{PVDF film, } k = 10) \quad .$$

For normal operation, 2.2 kV is applied across two 12 micron sheets of PVDF film. Therefore,

$$P = (1/2) \times 10 \times 8.9 \times 10^{-12} \text{ (F/m)} \times \left(\frac{2.2 \text{ kV}}{24 \times 10^{-6} \text{ m}}\right)^2$$

$$P = 3.7 \times 10^5 \text{ nt/m}^2 \quad ,$$

expressed in atmospheres

$$P = 3.7 \text{ atm} = 56 \text{ psi} \quad .$$

In conventional films, k is in the range of only 2 to 3. This relatively high mechanical pressure in K-F film may cause cracking, stretching, or punctures if a 1-10 micron dia particle is trapped between the layers.

Also, the electrostatic field redistribution within these hypothetically contaminated layers of film and foil may be more lethal when the film has high k because most dust has k between 2 and 6. The dust may undergo electrical breakdown due to the field enhancement and, therefore, cause breakdown of the contiguous film.

2-4 FILTERED ENCLOSURE

To assist in the evaluation of airborne contamination, we hired a consultant, Modulaire Inc., to evaluate the particle density and recommend methods for upgrading the clean-room quality. They assisted in making particle density measurements.

Prior to making this measurement, we installed a laminar flow bench next to the winding machine which was used for the manufacture of PVDF film capacitors. This bench contains a blower and filter which allows filtered air to be emitted horizontally away from the bench. In this way, it was possible to immerse the winding machine in the filtered air from the bench. The bench and winding machine were located in the large clean room in which Maxwell manufactures all capacitor windings. An important objective of the particle density measurement was to compare dust particle densities with and without the laminar flow bench turned on.

Table 2-2 summarizes the results of the measurement. As shown, the particle density of 0.5 micron dia particles is about 360/ft^3 when the laminar flow bench is turned on compared to 1100/ft^3 when off. Further improvement in this count will occur when small leakages in the main wall filters of the clean room are repaired.

TABLE 2-2
PARTICLE DENSITY IN MAXWELL WINDING ROOM--MEASUREMENTS BY MODULAIRE WITH MET ONE, INC., INSTRUMENTATION. MEASUREMENT WAS MADE ON NOVEMBER 4.

Location of Modulaire Probe	Sample Rate ft^3/min	Maxwell Static Eliminator	Laminar Flow Bench	Density of (parts/ft^3)			Notes
				0.5	1.0	5.0	
On winding machine	1	ON	ON	360	200	3	
Same	1	ON	OFF	1,100	520	6	
On laminar flow bench	1	ON	ON	100	---	---	Depended on location. Some leakage was evident.
Outside and above laminar flow bench	1	---	---	1,100	790	---	This reflects general room quality.
Near large wall filters	1	---	---	100's to 1,000's	---	---	Depends on probe distance from damaged filters.

Consequently, we enclosed the winding machine and laminar flow bench with a plastic sheet in order to permit the bench to continuously upgrade the air quality in the volume surrounding the winding machine. Also, the small leaks in the main filters were repaired. Then, we proceeded with the manufacture of the PVDF/paper/castor oil capacitor windings.

2-5 EXTRAPOLATION OF LIFE

An important relationship used in all extrapolations in this and the previous work, was the equation:

$$L_2 = L_1 \; (V_2/V_1)^{-a} \quad .$$

This equation is based on the empirical relationship*

$$L_2 = L_1 \; (E_2/E_1)^{3.5} (V_2/V_1)^{4} \quad ,$$

which results initially from capacitor failure data on mylar. For given material thickness, this equation becomes:

$$L_2 = L_1 \; (V_2/V_1)^{7.5} \quad .$$

During the previous development program, data on PVDF capacitors appeared to confirm the exponential dependence of life on voltage, but the exponent was in the range of 12-14 rather than the 7.5 for mylar. The data was obtained over the range 4-6 kV across 1 mil (two 12 micron films) of PVDF. This field of 4-6 kV/mil is close to the intrinsic breakdown strength of the material and extrapolations to the rated field of 2.4 kV/mil may be invalid.

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*Based in part on private conversations with P. Hoffman, capacitor consultant to Maxwell Laboratories.

SECTION 3

TEMPERATURE COMPENSATION

The volumetric expansion of the capacitor constituents must be provided for, to allow the sealed capacitor to span the temperature range of -20°C to +50°C. To meet this requirement Maxwell enclosed a specially sealed bellows assembly in the vacuum qualified capacitors.

To review the basis for this requirement, consider a capacitor which does not include volume compensation. During the final step of manufacturing, the fully impregnated capacitor is cooled to a temperature slightly below the minimum operating temperature. In our case, this would be about -25°C. In preparation for cooling, the fill hole of the capacitor is connected to a funnel which is filled with impregnant. As the capacitor cools, the contracting liquid within the capacitor draws in additional liquid from the funnel. Then, the fill hole is permanently sealed. As the capacitor warms, thermal expansion of all the constituents occurs, which tends to increase pressure inside the can.

3-1. THERMAL EXPANSION OF CAPACITOR CONSTITUENTS

The attached Table 3-1 shows a detailed listing of all constituents, their volumetic coefficients, and the expansion which occurs for temperature change of 70°C. First, consider a silicone impregnated capacitor. As shown, the silicone oil has a high expansion coefficient and is a major factor in the pressure rise, contributing about 50 percent of the volume change. The K-F film itself contributes an equal amount.

Using a liquid with a volumetric coefficient equal to that of other impregnants (about $0.7 \times 10^{-3}/°C$) would not avoid the pressure rise. Note, Items 1 through 7 in the table tend to increase internal pressure while Item 8, which shows the increase

TABLE 3-1
EDWARDS AFB ANALYSIS OF
THERMAL EXPANSION IN K-F FILM CAPACITORS

	Constituent	$\alpha \frac{1}{^oC}$	$\gamma \frac{1}{^oC}$	Weight[7,8] (g)	Weight[7,8] (lbs)	Density $\rho g/cm^3$	V_1 cm^3	ΔV (ΔT = 70°C) cm^3
1	Aluminum foil	25.0×10^{-6} [1]	75.00×10^{-6} [2]	418	(0.92)	2.70	155	0.81
2	PVDF (K-F) film	12.0×10^{-5} [3]	36.00×10^{-5} [2]	1282	(2.82)[8]	1.80	712	18.40
3	PVC (tubular core)	5.0×10^{-5} [3]	15.00×10^{-5} [2]	50[5]	(0.11)	1.50	33	0.35
4	Polypropylene core plug	9.7×10^{-5} [3]	29.00×10^{-5} [2]	30[5]	(0.07)	0.90	33	0.67
5	Silicone oil	------	1.05×10^{-3} [4]	247[6]	(0.54)	0.94	263	19.30
6	Tabs, end and wrap			85	(0.19)			Nil
7	Stainless 304	20.0×10^{-6}	60.00×10^{-6}	545	(1.20)	7.60	1130	4.75

[1] Handbook of Chemistry and Physics
[2] Estimated with 3α
[3] Plastics 1980 Desk Top Data Book B
[4] Dow Corning Product Data
[5] Measured value
[6] Calculated value
[7] Total capacitor wt = 2657 ± 40 g
[8] Measured dry winding wt = 1725 g

α = linear coefficient of thermal expansion
γ = volume coefficient of thermal expansion
V_1 = initial volume

in case volume, tends to decrease pressure. Unfortunately, the case increases by only about 5 cm^3 while the constituents increase by about 40 cm^3.

These estimates were verified experimentally. A capacitor case was filled with a PVDF film winding and silicone oil impregnant. It was then heated from 25°C to 85°C and the depth of liquid in the can was observed to change by 0.12 in. This depth change was equivalent to a volume change of 25 cm^3. For a 70°C change, that would have been about 30 cm^3 compared to the change of 35 cm^3 (40 cm^3 for the components minus 5 cm^3 for the can) predicted from the table. Since the tabulated volumetric coefficients were estimates, that is good agreement.

3-2 FLEXIBLE LID

We had incentive to employ the same flexible lid technology which resulted in the case used during the previous program. It was hoped that by making the lid thinner and carefully adjusting the stress within the lid, we could take up the required volume. This idea was attractive, because it appeared to be relatively simple and could be done with only minor impact on the present Hardness Demonstration Program.

Unfortunately, we were not able to design a satisfactory lid which could attain the required volume change. Table 3-2 shows the calculated influence of lid thickness and stress on deflection. We allowed a maximum hydrostatic pressure of 50 psi within the capacitor, at which point the lid is extended by the axial deflections as shown. To attain 32 cm^3 of additional volume, an 0.8 cm deflection is required in our 10 cm (4 in.) dia capacitor cans.

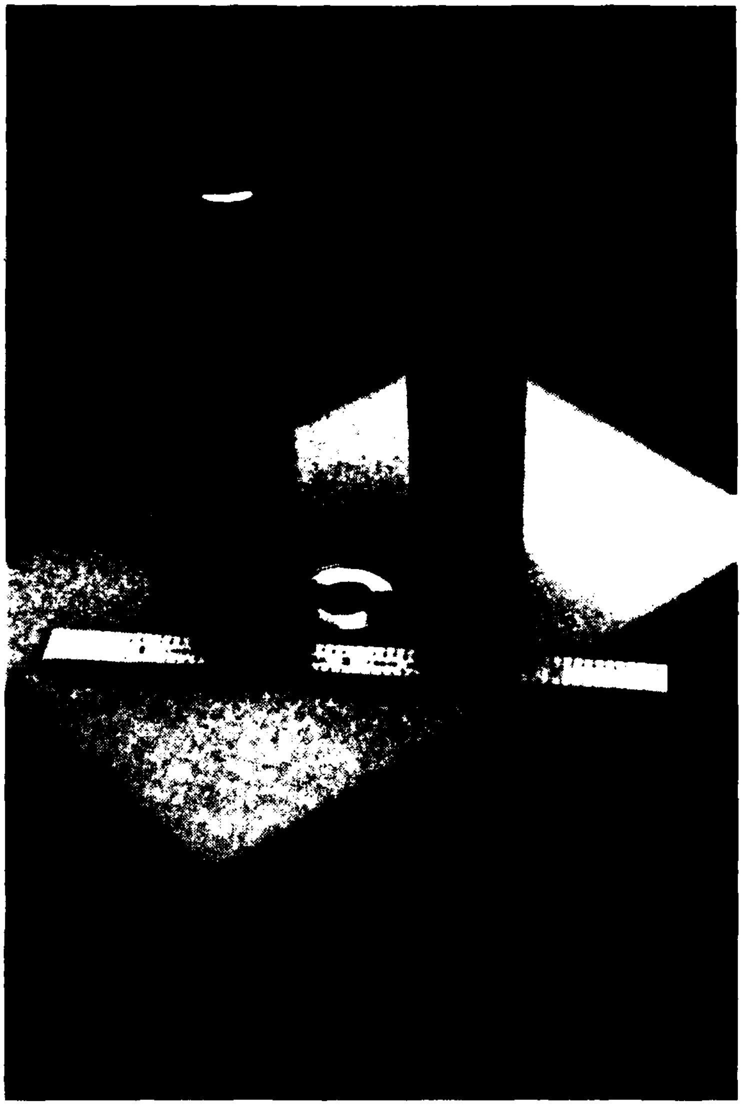
We cannot exceed 80,000 psi within the lid material because of possible fatigue failure prior to the life requirement of 10,000 cycles. (This cycle life was estimated by assuming 2 cycles per day for 10 years).

TABLE 3-2
STAINLESS 301, FULLY COLD WORKED

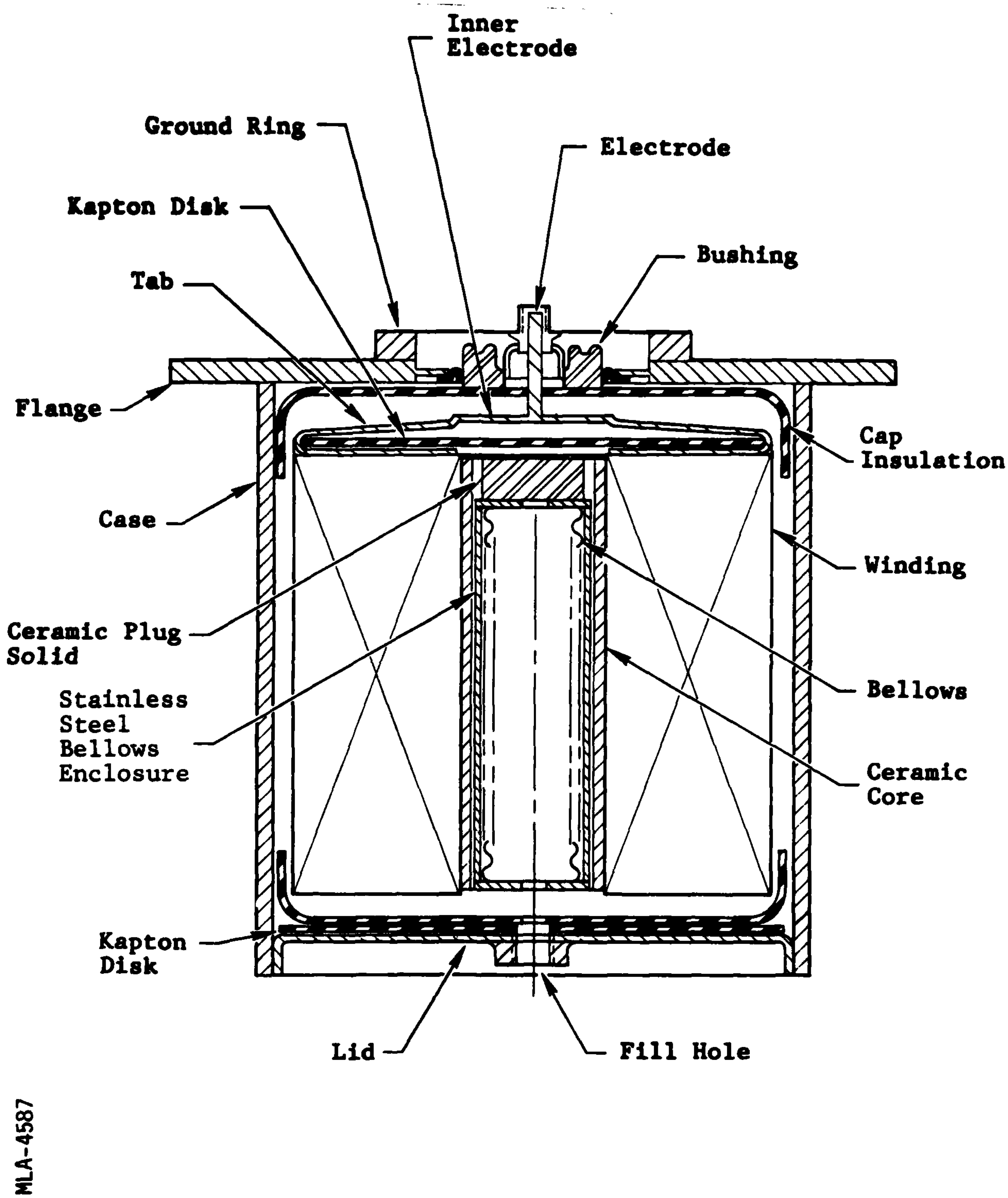
Thickness (mil)	Deflection (cm)	Stress (Ksi)
15	0.220	76
10	0.254	88
5	0.320	120

3-3 BELLOWS

Therefore, we turned to a bellows approach. We now have a 30 cm^3 volume within the capacitor occupied with a polypropylene plug which fills the void within the tubular winding core. In a similar geometry, Dr. G. H. Mauldin of Sandia Corporation has successfully used welded stainless bellows manufactured by Metal Bellows Company of Sharon, Massachusetts. We have been in contact with this company and have been assured they can provide bellows of spacecraft quality. Figure 3-1 shows a bellows and a tube in which the bellows will be confined, and Figure 3-2 shows the position of the bellows within the capacitor.



3-1. Bellows and tubular enclosure.



3-2. Design of capacitor containing bellows assembly.

SECTION 4

CAPACITOR TEST EQUIPMENT

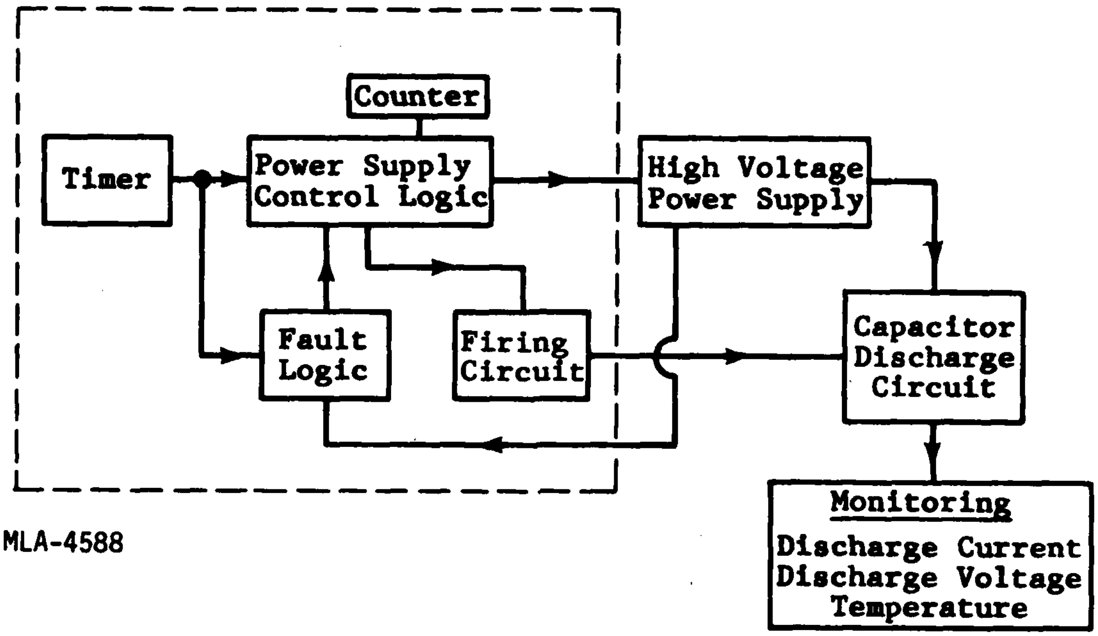
The capacitor test facility is a modified Maxwell MAGNEFORM 7000 machine. A block diagram of the test facility is shown in Figure 4-1 and maximum operating parameters are given in Table 4-1. The maximum peak discharge current as a function of ringing frequency is given in Figure 4-2; and the maximum repetition rate of which the system is capable, as a function of peak current, is given in Figure 4-3. This facility proved to be extremely reliable throughout the capacitor test program. Following is a summary of the main characteristics.

The capacitor test facility may be divided into these major sections:

- Charge control and firing logic
- High voltage power supply
- Discharge circuit
- Monitoring circuits.

The charge control and firing logic contains:

- A timer which sets the time between shots
- A shot counter
- The power supply control logic. This unit starts charge, stops charge when the power supply has reached set voltage, and sends a low level fire command to the trigger generator.
- The trigger generator. This unit sends a high level fire command to the ignitions in the discharge circuit.
- Fault logic.



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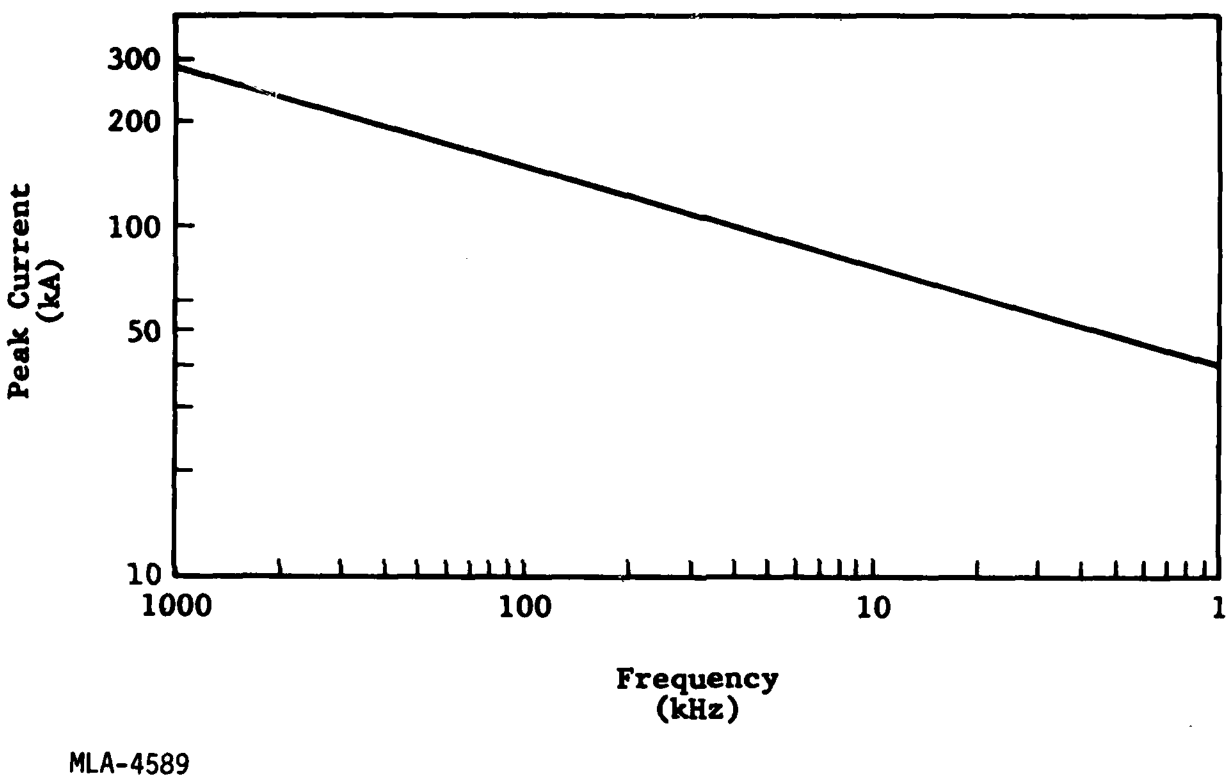
4-1. Block diagram of capacitor test facility.

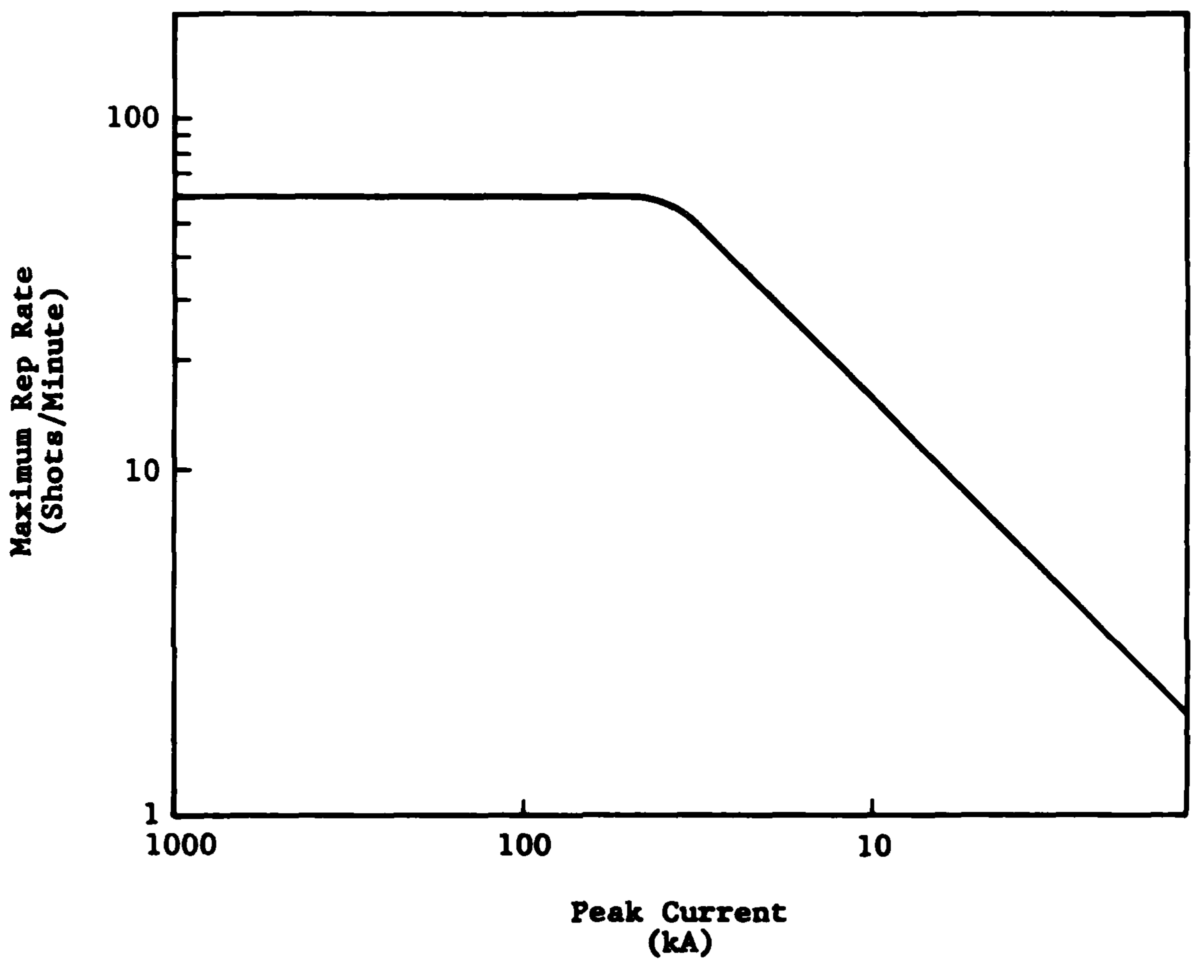
TABLE 4-1

CAPACITOR TEST FACILITY SPECIFICATIONS

SPECIFICATION	GOALS
Maximum charge Voltage	10 kV
Maximum charging current	1 A
Maximum discharge current	See Figure 4-3
Maximum repetition rate	See Figure 4-4
Maximum current reversal	100%
Maximum number of capacitors that may be tested in parallel	2
Maximum capacitor size	8 x 14-1/2 x 22-1/2 in.
Power requirements	
Voltage current	208 single phase 60 A
Machine size	34 x 40 x 35 in.
Diagnostics	Charge voltage Charge current Discharge voltage Discharge current Capacitor temperature



4-2. Peak current versus ringing frequency.



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4-3. Maximum repetition rate versus peak current.

A desirable feature of a capacitor test facility is the capability to operate unattended 24-hours per day. Therefore, logic was installed that shut down the facility if any abnormalities in the charging cycle occurred. The test facility shuts down if any of the following occurs:

- The load becomes disconnected from the high voltage power supply

- The high voltage power supply becomes shorted

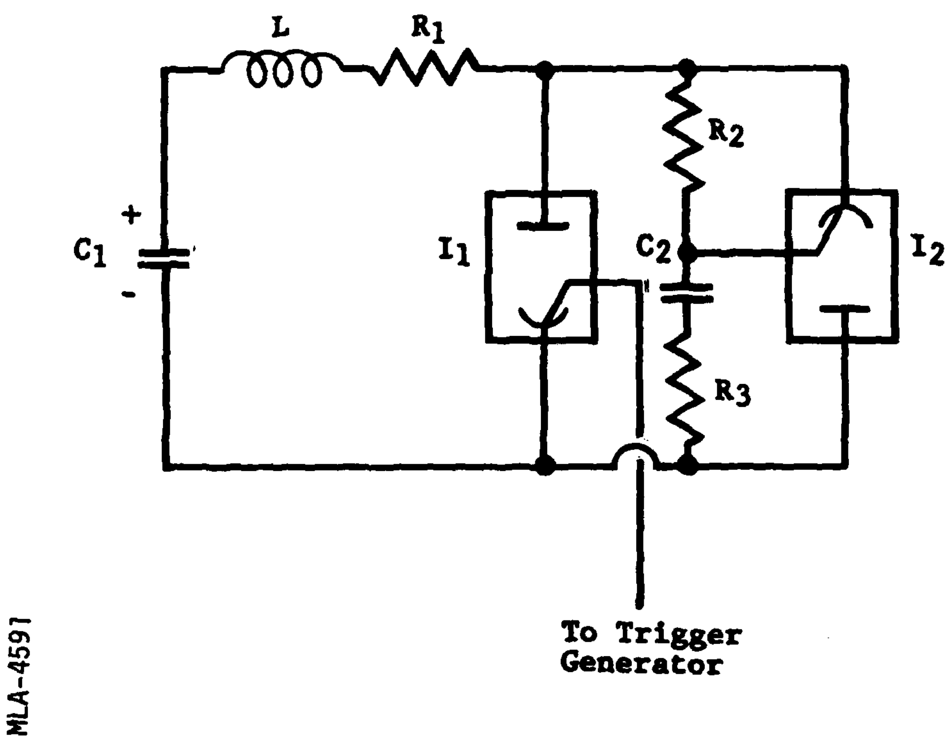
- The high voltage power supply charges above the set voltage point

- The capacitor remains charged after the trigger command is given.

Several different capacitor faults have occurred and the facility has shut down safely.

The power supply which charges the test capacitor is capable of a maximum voltage of 10 kV and a maximum charging current of 1 A. The charge current is conveniently controlled by reactance capacitors placed in the primary of the transformer.

A diagram of the discharge circuit is shown in Figure 4-4. The resistance and inductance is variable to establish the desired voltage discharge waveforms and current discharge waveforms. The switch consists of back-to-back ignitrons. This arrangement allows high current reversal without damage or malfunction of the ignitrons.



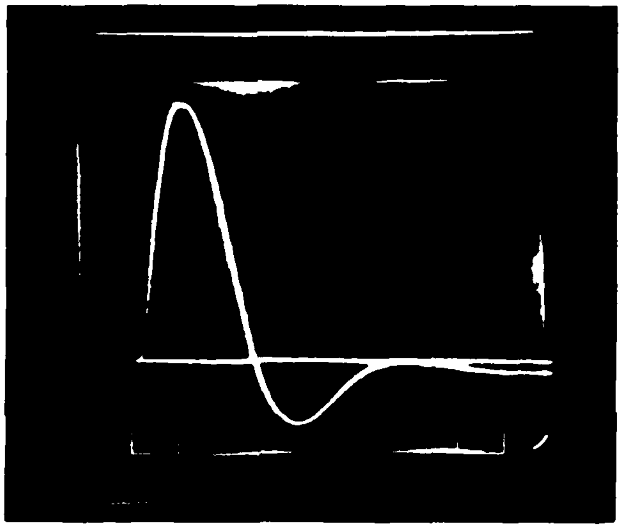
4-4. Capacitor discharge circuit.

The facility has the capability of monitoring:

- Charging voltage
- Charging current
- Discharge voltage
- Discharge current
- Capacitor temperature.

The charging voltage is monitored on a shot-to-shot basis using a strip chart recorder. This shows any variation in charging voltage and provides a backup to the shot counter. The charge voltage monitor is calibrated against a reliable electrostatic voltage meter.

Figure 4-5 shows a discharge current waveform taken with capacitor (Number 11) charged to 3.8 kV. The peak current is 52.4 kA with 25 percent reversal. Figure 4-6 shows the capacitor charging waveform during a typical 3.2 kV test.



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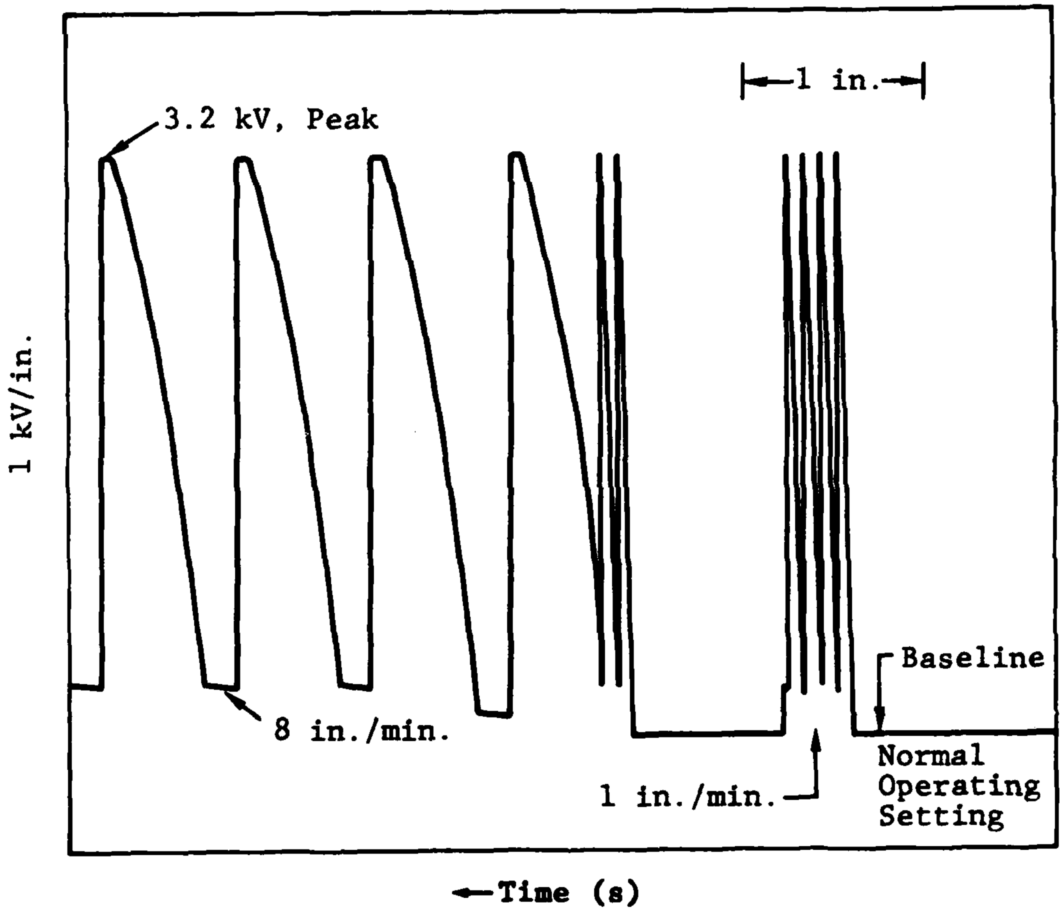
4-5. Discharge current of capacitor (Number 11) charged to 3.8 kV. The peak current is 52.4 kA with 25 percent reversal. The ringing frequency is 40 kHz.



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4-6. Strip-chart record of capacitor charging voltage at 1 in./minute (right-hand side) and 8 in./minute (left-hand side).

SECTION 5

CONSTRUCTION OF PVDF/PAPER/CASTOR OIL TEST CAPACITORS

In accordance with the plan described in Section 2, a group of capacitors was manufactured for discharge-life tests at accelerated voltages. A total of twelve 70 μF test capacitors (in standard steel cases) were manufactured:

- Five underwent discharge-life testing at Maxwell.
- Four are being tested at AFRPL.
- Two were rejected.
- One is a spare.

These 70 μF capacitors consist of PVDF film/paper/castor oil in conventional steel cases. Table 5-1 summarizes the present status of each capacitor.

This section discusses those aspects of the manufacturing procedure which are substantially different from those employed in the vacuum-qualified capacitors. The next section describes the detailed construction procedure of the vacuum-qualified capacitors.

The following three differences exist between the manufacturing of the vacuum-qualified capacitors and the test capacitor.

5-1 VACUUM QUALIFIED COMPARED TO TEST CAPACITORS

a. Bellows. The test capacitors do not contain bellows assemblies for temperature compensation. These test capacitors are sealed at about 15°C, a temperature slightly below room temperature. They are allowed to heat to about 35°C during discharge tests. Through this temperature range, thermal compensation is not mandatory.

TABLE 5-1
STATUS OF TEST CAPACITORS

Test Number	Serial Number	Shots	Voltage (kV)	Status
1	140092	218,104	3.2	Intact.*
2	140093	218,104	3.2	Failed and autopsied
3	140094	121	2.8	Shipped to Edwards
4	144095	+121	2.8	Shipped to Edwards
5	140096	43,345	3.8	Body failure
6	140097	-0-	---	Failed leak inspection
7	140098	100	3.5	Shipped to Edwards
8	140099	100	3.5	Shipped to Edwards
9	140100	23,922	3.8	Not valid data point --center stud eroded away
10	140101	85,936	3.8	Body failure (bushing shows signs of leakage)
11	140102	18,668	3.8	Failed and autopsied (Two failure points. Inside diameter and outside diameter of winding).
12	140103	-0-	---	Available for Maxwell or AFRPL test

*Subsequently failed after one charge. Suspect improper charge voltage.

b. Case. The test capacitors are enclosed in a standard steel case in order to preserve the expensive stainless steel capacitor cases for the vacuum-qualified capacitors.

c. Core. The test capacitors were wound on a delrin core with OD of 1.3 cm (0.5 in.). The vacuum-qualified capacitors use an alumina core with OD of 3.8 cm (1-1/2 in.) which contains the 1-1/8 in. OD bellows housing. The ceramic is capable of withstanding required radiation levels in the vacuum-qualified capacitor.

5-2 WINDING FACILITIES

Elimination of airborne contamination in the winding room is essential in the manufacture of capacitors which use films with high dielectric constant. A laminar flow bench was installed next to the machine used for winding PVDF film capacitors. The machine and bench were contained in a plastic enclosure, in order to allow the bench filters to continuously upgrade the quality of air surrounding the equipment. Also, the enclosure contained our standard static elimination equipment.

The capacitors were constructed from 9 micron (35 g) PVDF film, 6.4 micron (25 g) Kraft paper and 5.8 micron (23 g) aluminum foil. The dielectric between a pair of aluminum foil electrodes consisted of two sheets of PVDF film which were separated by one sheet of paper. The detailed specification is shown in Items 1.0 through 1.3 in Appendix C. Following winding and installation in cans, the capacitors underwent vacuum impregnation with castor oil.

5-3 QUALIFICATION TESTING

Each capacitor manufactured under this program underwent qualification testing. The qualification test procedure described in Appendix A was followed in the preparation of Table 5-2 which summarizes the test results. The vacuum leak

test described in the qualification test of Section 7-2 was not followed for capacitors in standard steel cans.

The acceptance test record of those capacitors in standard cans which were shipped to AFRPL is shown in Tables 5-3 through 5-6.

TABLE 5-2

CAPACITOR QUALIFICATION TEST AND FINISHED GOODS REPORT

Sales Order No. Edwards Job No. 11-8622 Catalog No. 34251 Spec. No. Special

Serial Number	Prehipot Measurement CAP (μF)	Prehipot Measurement D.F. (%)	Hipot Voltage (kV)	Posthipot Measurement CAP (μF) @ 120 Hz	Posthipot Measurement D.F. (%)	Resonant Frequency (kHz)	Inductance (nH)	
140092	69.1	0.80	3.5	70.2*	0.85	136	19.8**	19.5
140093	69.5	0.80	3.5	70.2	0.87	134	20.3	20.1
140094	70.3	0.80	3.5	71.1	0.90	130	21.3	21.1
140095	70.0	0.78	3.5	70.7	0.88	134	20.2	20.0
140096	69.5	0.88	3.5	70.2	0.92	127	22.6	22.4
140097	70.4	0.80	3.5	71.2	0.89	129	21.6	21.4
140098	70.2	0.75	3.5	70.9	0.80	132	20.7	20.5
140099	70.4	0.85	3.5	71.2	0.91	133	20.3	20.1
140100	70.5	0.80	3.5	71.3	0.88	136	19.4	19.2
140101	71.5	0.78	3.5	72.3	0.85	128	21.6	21.4
140102	70.2	0.80	3.5	71.1	0.85	131	21.0	20.8
140103	71.1	0.85	3.5	72.1	0.88	130	21.1	20.8

* Mean and standard deviation, 71.0 ± 0.7

**Mean and standard deviaiton, L = 20.0 ± 0.9

TABLE 5-3
CAPACITOR ACCEPTANCE RECORD

Capacitor Serial Number 140094 Can Number 3

Lid Number --- Weight 5.0 lbs

Capacitance (25°C) 70.3 μF D.F. (25°C) 0.80

Leakage current 2.27 μA

Hipot performed at 3.5 kV dc for 60 s

Capacitor discharged once from 2.8 KF dc into 0.13 Ω resistance

Capacitor discharged one hundred times from 2.8 kV dc into 0.13 Ω resistance

Capacitance after discharge testing, 70.8 μF

Dissipation factor after discharge testing, 0.75 Percent

Inductance 21.3 nH

Leak test performed by heating capacitor to 50°C for 2 hours

Result: pass

Leak test performed by heating capacitor to 40°C for 1/2 hour at 100 microns pressure

Results: N/A

TABLE 5-4
CAPACITOR ACCEPTANCE RECORD

Capacitor Serial Number <u>140095</u> Can Number <u>4</u>

Lid Number <u>---</u> Weight <u>5.1 lbs</u>

Capacitance (25°C) <u>70.0 μF</u> D.F. (25°C) <u>0.78</u>

Leakage current <u>1.99 μA</u>

Hipot performed at <u>3.5 kV</u> dc for <u>60 s</u>

Capacitor discharged once from <u>2.8 KF</u> dc into <u>0.13 Ω</u> resistance

Capacitor discharged one hundred times from <u>2.8 kV</u> dc into <u>0.13 Ω</u> resistance

Capacitance after discharge testing, <u>70.5 μF</u> (12 hours)

Dissipation factor after discharge testing, <u>0.75 Percent</u> (12 hours)

Inductance <u>20.2 nH</u>

Leak test performed by heating capacitor to 50°C for 2 hours

Result: <u>pass</u>

Leak test performed by heating capacitor to 40°C for 1/2 hour at 100 microns pressure

Results: <u>N/A</u>

TABLE 5-5
CAPACITOR ACCEPTANCE RECORD

Capacitor Serial Number 140098

Can Number 7

Lid Number ---

Weight 5.0 lbs

Capacitance (25°C) 70.2 μF

D.F. (25°C) 0.75

Leakage current 2.00 μA

Hipot performed at 3.5 kV dc for 30 s

Capacitor discharged once from 3.2 KF dc into 0.013 Ω resistance

Capacitor discharged one hundred times from 2.8 kV dc into 0.013 Ω resistance

Capacitance after discharge testing, 70.6 μF (12 hours)

Dissipation factor after discharge testing, 0.75 Percent (12 hours)

Inductance 20.7 nH

Leak test performed by heating capacitor to 50°C for 2 hours

Result: pass

Leak test performed by heating capacitor to 40°C for 1/2 hour at 100 microns pressure

Results: N/A

TABLE 5-6
CAPACITOR ACCEPTANCE RECORD

Capacitor Serial Number 140099 Can Number 8

Lid Number --- Weight 5.1 lbs

Capacitance (25°C) 70.3 μF D.F. (25°C) 0.85

Leakage current 2.69 μA

Hipot performed at 3.5 kV dc for 60 s

Capacitor discharged once from 3.2 KF dc into 0.13 Ω resistance

Capacitor discharged one hundred times from 3.2 kV dc into 0.13 Ω resistance

Capacitance after discharge testing, 70.7 μF (12 hours)

Dissipation factor after discharge testing, 0.80 Percent (12 hours)

Inductance 20.3 nH

Leak test performed by heating capacitor to 50°C for 2 hours

Result: pass

Leak test performed by heating capacitor to 40°C for 1/2 hour at 100 microns pressure

Results: N/A

SECTION 6

MAXWELL TEST RESULTS

The serial status of each test capacitor manufactured during this program is shown in Table 6-1. The discharge-life data acquired at Maxwell is limited to five failed capacitors, (those indicated by an asterisk in the table). We anticipate additional data from the capacitors to be tested at AFRPL in the near future. To assist in the comparison of the data generated in the two laboratories, and to allow rough predictions of discharge life to be generated with the data now available, we have presented the data points on the Weibull plot shown in Figure 6-1.

6-1 DISCHARGE LIFE AT 3.8 kV

Three data points were obtained at 3.8 kV (test 5, 10, and 11 in the table). Of these, tests 5 and 11 were body failures. Test 10 survived the 85,936 shot life but the test was suspended because the seal at the high voltage output terminal developed a serious leak. The three points are plotted in Plot A as if the leaking seal constituted a failure. (High-voltage feedthrough is a serious problem in these high-current capacitors. It is important to distinguish between the feedthroughs on these standard cans from those on the vacuum qualified stainless cases. The standard cans have a soldered feedthrough which occasionally leaks after repeated high-current discharges. The stainless cans are equipped with a much stronger vacuum braze feedthrough.)

6-2 DISCHARGE LIFE AT 3.2 kV

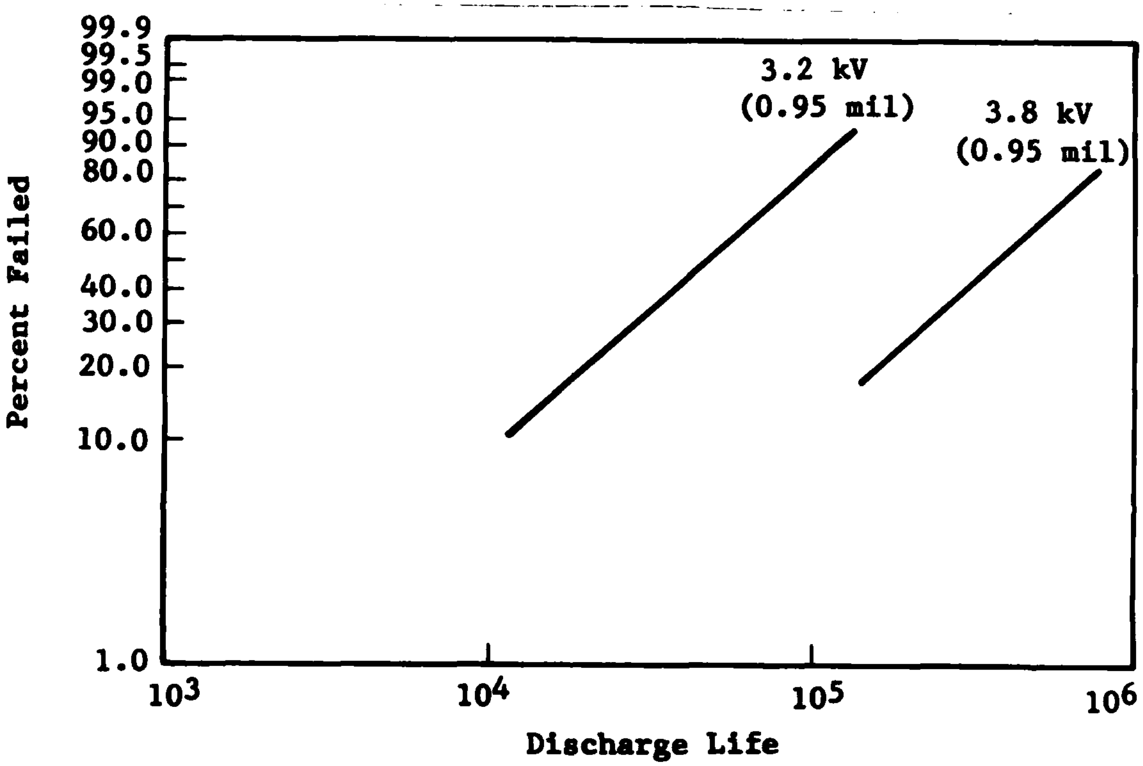
For the failure data at 3.2 kV, we have only two data points. Of these, the validity of test capacitor Number 1 (Table 6-1) is suspect because it failed immediately after the failure of test capacitor Number 2. We suspect the capacitor was brought to the voltage exceeding 3.2 kV after the removal of test

TABLE 6-1
STATUS OF TEST CAPACITORS

Test Number	Serial Number	Shots	Voltage (kV)	Status
1*	140092	218,105	3.2	Failed and autopsied**
2*	140093	218,104	3.2	Failed and autopsied
3	140094	121	2.8	Shipped to Edwards
4	144095	+121	2.8	Shipped to Edwards
5*	140096	43,345	3.8	Body failure
6	140097	-0-	---	Failed leak inspection
7	140098	100	3.5	Shipped to Edwards
8	140099	100	3.5	Shipped to Edwards
9	140100	23,922	3.8	Center-stud eroded away
10*	140101	85,936	3.8	Unfailed--leaking bushing (shows signs of leakage)
11*	140102	18,668	3.8	Failed and autopsied (Two failure points, inside diameter and outside diameter of winding).
12	140103	-0-	---	Available for Maxwell or AFRPL test

* Discussed in text

**Suspect overvoltaged



MLA-4593

6-1. Weibull plot of 3.8 kV and 3.2 kV capacitor failure data.

capacitor Number 1 from the test facility. Therefore, we assume test capacitor Number 1 had not yet failed; and we plotted the Weibull point as if one capacitor out of two failed, after both had sustained 218,104 discharges. To obtain the line B in Figure 6-1, we assumed the 3.2 kV slop equalled that obtained for the 3.8 kV data discharge. We believe this is caused by the gradual deterioration in the solder connection. This does not occur to the welded center stud in the vacuum-qualified capacitor.

These data are too limited to confidently draw conclusions from the Weibull plots, or from the estimated life versus voltage. However, it is interesting to do so, to compare the present failure points with those obtained previously. Also, it illustrates the technique.

Consider life versus voltage at the characteristic life (shown with a horizontal dash across the plots in Figure 6-1).

$$(L_1/L_2) = (V_1/V_2)^{-a}$$

$$= - \frac{\log (L_1/L_2)}{\log (V_1/V_2)}$$

$$= - \frac{\log (60{,}000/450{,}000)}{\log (3.8 \text{ kV}/3.2 \text{ kV})}$$

$$= 12 \quad .$$

Consider the extrapolated life at 2.4 kV. For the 70 μF capacitors manufactured for this program, this voltage would result in 190 J/capacitor. The extrapolated life L_2, using the 60,000 shots at 3.8 kV as the reference life L_1, is

$$L_2 = L_1 \ (V_2/V_1)^{-a}$$

$$= 60{,}000 \ (2.4 \text{ kV}/3.8 \text{ kV})^{-12}$$

$$L_2 = 1.4 \times 10^7 \text{ discharges} \quad .$$

The expected life at 99 percent reliability would be less than that estimated above. However, more data is needed before dependable Weibull plots can be obtained. Nevertheless, based on this data and the extrapolation, it appears that we have a capacitor capable of sustaining approximately the required 10^7 discharges for operation at 2.4 kV. To improve the estimate of the extrapolated life, we look forward to the results of the capacitor discharge tests and thruster life tests to be conducted at rated voltage by AFRPL.

SECTION 7
MANUFACTURE OF VACUUM-QUALIFIED CAPACITORS

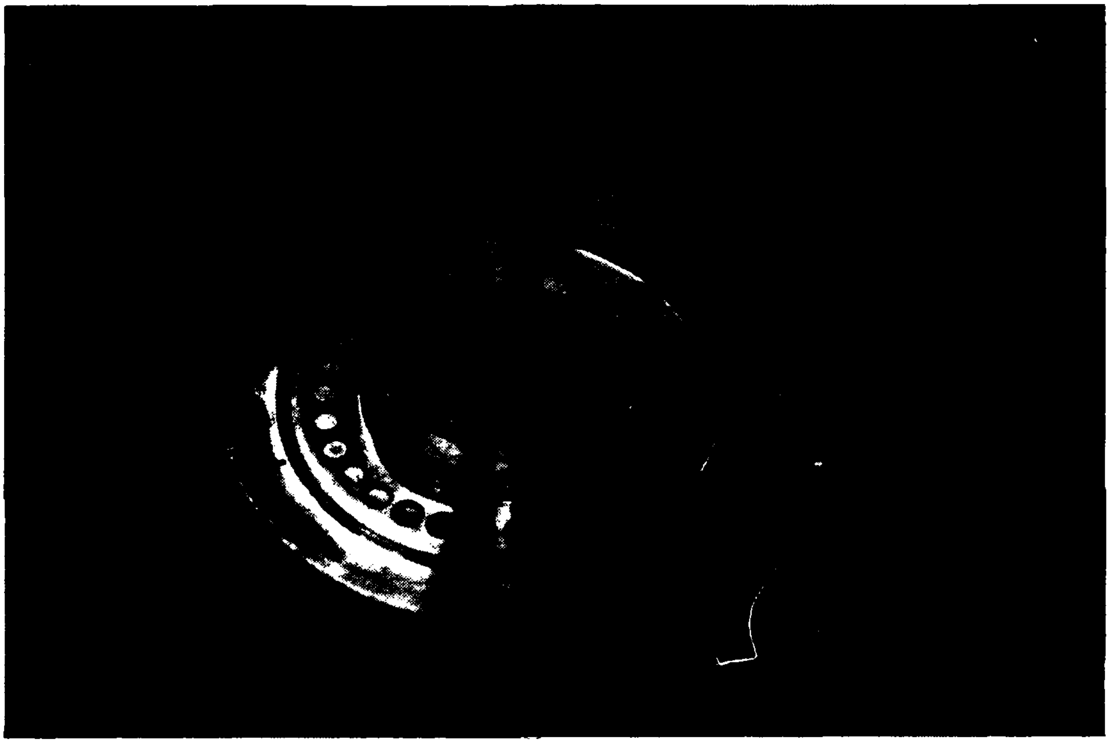
This section discusses Maxwell's manufacturing procedure for the fourteen vacuum-qualified, PVDF Film/paper/castor oil capacitors which were sent to AFRPL in accordance with the objectives of this program.

In summary, the manufacture of these capacitors includes the installation of the PVDF/paper winding into the special vacuum-qualified capacitor case provided under subcontract to Maxwell by Fairchild. This step is followed by welding of the can and impregnation with castor oil. Capacitor case manufacturing specification is contained in the report, "Specification for High Energy Density Pulsed Discharge Capacitor for Space Flight Application" by W. Guman and D. Palumbo, Number M300552300.

7-1 CAPACITOR CASE INSPECTION

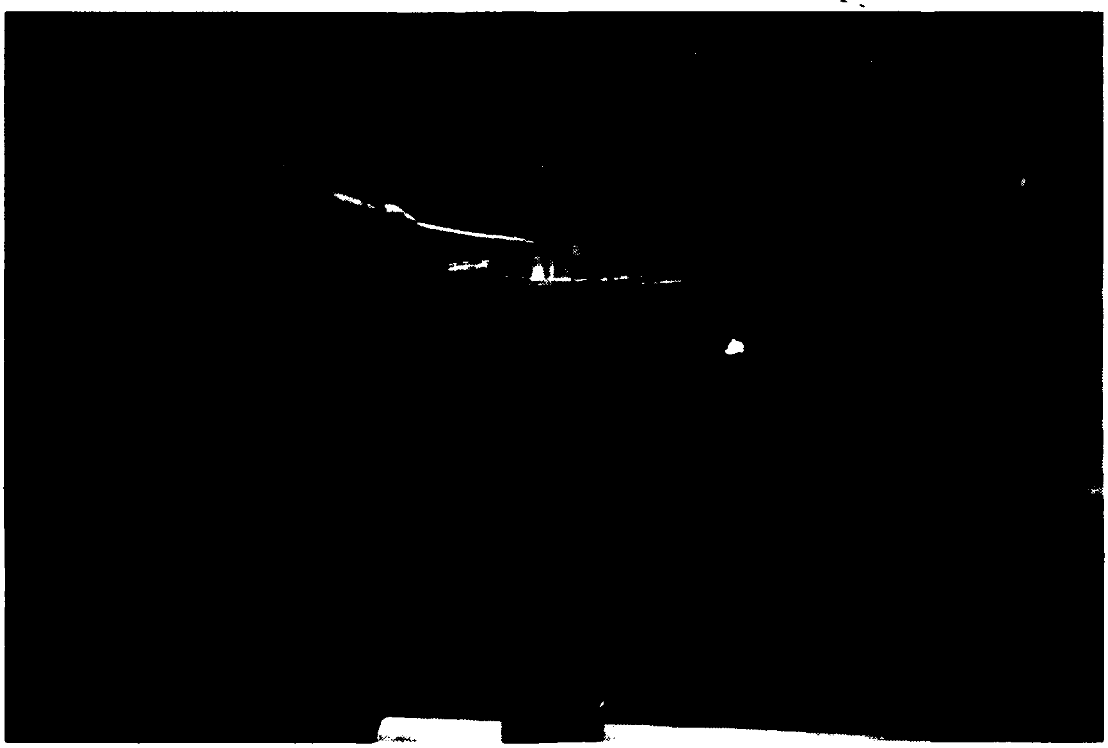
The vacuum brazes on the output bushing of the capacitor cases are carefully inspected. The capacitor case is shown in Figure 7-1. This inspection included a helium leak check. To perform this check, a special seal was made for the center stud as shown in Figure 7-2. The leak check was performed in two configurations. In one, the bushing area was evacuated while the interior remained at atmospheric pressure. This results in pressure in the same direction as that which occurs when the capacitor is in normal use under internal pressure. Helium was sprayed inside the case in the bushing area as shown in Figure 7-3. Then the case is evacuated on the inside and helium sprayed around the outside of the bushing. In this way, the pressure is opposite to that normally encountered during operation. No leaks were detected.

7-1. Capacitor case.


MLA-4595

7-2. **A special seal was made for the center stud.**

MLA-4596



7-3. Helium leak check of capacitor case.

7-2 WINDINGS

Windings were constructed using the same materials as in the test capacitors. As before, the winding procedure called for the minimium winding tension in order to minimize the mechanical pressure applied to the PVDF film. Also, all winding was performed in the special air-filtered enclosure. Also, the extended-foil soldering operation was performed in the same dust-free enclosure. This enclosure contains a winding machine and laminar flow bench. In this way, the winding environment was maintained with the airborne particle count of <100 parts/ft^3 of 1 micron diameter. All handling operations were performed with particular attention towards minimizing contamination of the winding. Figure 7-4 shows the swagging operation of the extended foils.

7-3 ASSEMBLY

After insertion of the winding into the capacitor case, the center pin electrode of the capacitor winding was welded into the center stud of the capacitor case. Then, the leak check of the center-stud assembly was repeated (without the special O-ring seal discussed above). Three capacitors were found to leak. One was rewelded and then passed inspection. The other two (Serial Numbers 142527 and 142534) leaked and were soldered in order to make a seal. These two capacitors may serve as spares in future tests. Qualification tests of these capacitors are shown in Table 7-1.

7-4 BELLOWS

All bellows were leak checked. The bellows contain a partial pressure of helium, and even small leaks would have been readily detected with our helium leak detector. Also, deflection tests were performed on all bellows. This test was performed by measuring the force required to deflect the bellows by 15/16 in. This force varied by several ounces from one bellows assembly to another. The approximate force was about 6-1/2 lbs. The exact

MLA-4597

7-4. Swagging of extended foils.

TABLE 7-1
CAPACITOR QUALIFICATION TEST OF VACUUM QUALIFIED
CAPACITORS IMPREGNATED WITH CASTOR OIL

SALES ORDER NO. 14685 JOB NO. 011-8622-00 CATALOG NO. 34252 SPEC. NO. 350203-25202

	Serial Number	Leak Check 50 °C (1 ATM)	Post-Impreg.		Hipot Voltage 30 s (kV)	Post-Hipot		Leakage Current (A)	Post-100 Discharges		Leak Check 50 °C, (V ac)	Resonant Frequency		
			Cap (µF)	D.F. (%)		Cap. (µF)	D.F. (%)		Cap. (µF)	D.F. (%)		F_o kH	L (nH)	Weight
1	142527 (S)	Pass	66.1	0.70	3.5	66.8	0.80	41	66.5	0.75	Pass	94	43	5 lb, 9 oz
2	142528	Pass	67.1	0.70	3.5	67.8	0.85	37	67.8	0.75	Pass	125	24	5 lb, 10 oz
3	142529	Pass	67.2	0.70	3.5	68.0	0.85	37	67.9	0.80	Pass	120	26	5 lb, 10 oz
4	142530	Pass	67.1	0.75	3.5	67.9	0.80	37	67.9	0.80	Pass	120	26	5 lb, 10 oz
5	142531	Pass	67.1	0.70	3.5	67.9	0.85	37	67.9	0.80	Pass	116	28	5 lb, 10 oz
6	142532	Pass	67.0	0.70	3.5	68.2	0.85	40	67.9	0.80	Pass	117	27	5 lb, 10 oz
7	142533	Pass	67.5	0.75	3.5	68.2	0.85	32	68.0	0.80	Pass	110	31	5 lb, 9 oz
8	142534 (S)	Pass	67.1	0.75	3.5	68.1	0.80	37	67.9	0.75	Pass	106	33	5 lb, 9 oz
9	142535	Pass	67.0	0.75	3.5	67.8	0.85	37	67.8	0.80	Pass	108	32	5 lb, 9 oz
10	142536	Pass	67.1	0.80	3.5	67.9	0.85	39	67.9	0.85	Pass	94	42	5 lb, 9 oz
11	142537	Pass	67.1	0.70	3.5	67.9	0.85	37	67.9	0.85	Pass	120	26	5 lb, 10 oz
12	142538	Pass	67.0	0.75	3.5	67.8	0.80	35	67.5	0.80	Pass	92	44	5 lb, 10 oz
13	142539	Pass	66.8	0.70	3.5	67.2	0.75	39	67.2	0.80	Pass	116	28	5 lb, 10 oz
14	142540	Pass	67.1	0.70	3.5	67.8	0.80	37	67.9	0.80	Pass	113	29	5 lb, 10 oz

(S) - Spare

measured forces from each bellows was scribed into the welded sleeve assembly which confines the bellows. The forces and corresponding capacitor case serial numbers were recorded for future reference. This will allow comparison of deflection force in the future with the present values to detect changes. Significant changes in deflection force would occur if the bellows leaked. Figure 7-5 shows the bellows in its enclosure.

7-5 QUALIFICATION TESTING

The procedure outlined in Appendix A was followed in the performance of the qualification tasks. The results are summarized in Table 7-1. Those capacitors marked "(S)" (142527, and 142534) have soldered center studs instead of the welded center studs in the other capacitors. The soldering was required because center-stud leaks were discovered during leak checks. This leak check was performed when the winding was in place inside the case, in preparation for impregnation with castor oil. We believe these two capacitors will perform normally; but they should, nevertheless, be reserved as spares.

MLA-4598

7-5. Bellows in its enclosure.

SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions drawn from this program are the following:

- The 80 μF all-film, PVDF capacitors impregnated with silicone oil do not have a linear voltage coefficient of life in the range of 2.2-3.9 kV.

- Although the root cause of failure has not been identified with certainty, a probable cause is that the silicone oil interacts with the PVDF and causes polymerization and gases. This reaction may be accelerated by high-voltage conduction in the silicone oil during the charge and discharge of the capacitor. Even without such interaction, the discontinuity in dielectric constant between the PVDF and the impregnant may be detrimental, and lead to initial breakdowns in the dielectric fluid which then leads to early failure of the PVDF.

- These problems are avoidable using a PVDF/paper capacitor impregnated with castor oil. These capacitors appear to fail due to foil cracking. These cracks occur due to the flexing of the capacitor as it is charged and discharged. In this mode, small sparks appear across foil cracks. These sparks eventually erode the contiguous PVDF film leading to failure.

- Despite the improved life of PVDF/paper/castor oil capacitors, body failures persist and edge wear appears minimal. From this, we conclude that we

should be capable of still longer life if the mechanism causing body failures could be dealt with. The low dielectric constant in the paper/castor oil, compared to that of PVDF is probably contributing to failures. With higher dielectric constant impregnant, life could be dramatically extended.

To meet the radiation requirements of thruster capacitors, we must consider the use of all-film capacitors. We have performed autopsies on all PVDF/paper/silicon oil capacitors tested during this program and on several all-film PVDF capacitors manufactured during the previous technology program. In each case, we attempted to evaluate the precise cause of failure and develop a correction. On occasion, we found a manufacturing defect and the cause of failure was reasonably clear. In the vast majority of cases, there was no such defect and the actual cause or mechanism of failure remained unclear. This is particularly true in the AFRPL capacitors; such extreme care was taken in their fabrication, that obvious defects were rare. In part, this difficulty was caused by the destruction of the material surrounding the point of failure. We are now beginning to develop the capability to evaluate sections of a failed capacitor which are remote from the point of failure, to determine other points which are close to failure. On the PVDF/paper/castor oil capacitors, we are approaching this understanding after observing that foil cracking and consequential arc damage do occur in many areas of the failed capacitor remote from the actual failure point.

In future tests, we will perform more detailed chemical and physical analysis of the capacitor residue as described in Section 2. In this way, material degradation would be identified. In some cases, these analyses must be performed after discharge/tests (but prior to failure) to evaluate the capacitor contaminants prior to occurrence of failure.

We believe creases which develop during the life of the capacitor are detrimental, because eventually the foil breaks and separates leading to arcing which bridges the creases. This appears to cause erosion of the film, leading to failure.

The creases are thought to be primarily caused by the physical (piezoelectric) nature of the PVDF film and cannot be totally avoided. We believe failure, due to creases in the all-film capacitors, is not the main cause of failure, but would eventually occur if the capacitor life went into the 10^6 to 10^7 shot range. Mechanical design change may reduce the wrinkling; for example, a slightly oval capacitor may have less wrinkling than a round one. A capacitor with a smaller ratio of outer-to-inner diameter may also have less wrinkling.

Throughout the current and the previous programs, we have focused on all-film capacitors to meet the radiation resistance requirements. Another option is to introduce a radiation resistant paper substitute between the films. We searched for such a substitute, but were frustrated in this search because all promising, absorbent compositions we checked were too thick or porous to be useful. This concept has not yet been discarded at this time.

It is apparent that some design change may be necessary to have all-film capacitors meet requirements. For the present, we are optimistic that the PVDF/paper/castor oil capacitors shipped to AFRPL, will be reliable for the future thruster experiments.

SECTION 9

REFERENCES

1. "Development of a High Energy Density Capacitor for Plasma Thrusters", A. Ramrus, AFRPL-TR-80-35 under Contract No. F04611-77-0045.

2. The PVDF film used by Maxwell is manufactured by the Kureha Corporation, Japan. It is often referred to as K-F film.

3. Discharge lives are plotted on Weibull paper from which the "characteristic life" or life at 37 percent survival is obtained. The life at 99 percent survival is also obtained from the same plot. For further discussion, see: "Introduction to Weibull Analysis", Pratt & Whitney Aircraft Report PWA 3001, January 6, 1967.

4. Autopsy reports are as follows:

   - Capacitor Number 111098, MLR-1022, 13 February 1981
   - Capacitor Number 111093, MLR-1031, 18 February 1981
   - Capacitor Number 111099, MLR-1066, 30 April 1981
   - Capacitor Number 140093, MLR-1238, 10 March 1982

APPENDIX A

CAPACITOR ACCEPTANCE PROCEDURE

ACCEPTANCE PROCEDURE

FOR

80 μF, 2.2 K-F FILM , PLASMA THRUSTER CAPACITORS

A. <u>Test Procedure</u>

1.0 Weigh and record weight of each capacitor.

2.0 Measure capacitance and dissipation factor at 120 Hz on G. R. 1617A capacitance bridge. (Use double leads or straps for accurate D.F. measurement.)

3.0 Measure insulation resistance at room temperature at rated voltage.

3.1 Measurement procedure:

3.1.1 Measure capacitance (with 120 Hz bridge)

3.1.2 Charge capacitor to rated voltage. Use electrostatic voltmeter to measure capacitor voltage.

3.1.3 Leave power supply connected to capacitor and hold voltage at rated value for three minutes. Then disconnect power supply from capacitor but leave electrostatic voltmeter connected to capacitor.

3.1.4 Obtain voltage measurements at 10 s intervals for at least three minutes.

3.1.5 Discharge capacitor into load dump resistor of about 10 kΩ.

3.2 Analysis

3.2.1 Apply formula for exponential decay:

$$V/V_o = e^{-t/\tau}$$

where:

V_o is initial charge voltage (rated).

V is voltage at time t.

τ is effective shunt resistance, R, times the measured capacitance, C.

3.2.2 Risetime may be calculated from the above formula or from the following equivalent formula:

$$R = \frac{-t}{C \ \ell n(V/V_o)}$$

where ℓn is natural log.

3.2.3 Initial leakage current is given by the formula:

$$\hat{I}_L = V_o/R.$$

4.0 Hipot test

4.1 Hipot to 3.5 kV dc for 60 s. Start timing when 3.2 kV is reached. After specified time period turn off voltage, discharge capacitor through resistor of at least 1 Ω.

4.2 Hipot to 2.5 kV for 5 s and discharge as in 4.1.

5.0 Remeasure and record capacitance and dissipation factor as in 2.0.

6.0 Measure capacitor inductance

6.1 Measurement procedure

6.1.1 Attach low inductance electrodes to output bushing

6.1.2 Connect oscillator, HP 200 CD or GR 1310A, to the capacitor. Ground lead of oscillator is connected to ground ring of capacitor. Output lead of oscillator is connected to center stud of capacitor. Use coaxial lead (RG58) for connection from oscillator to capacitor.

6.1.3 Attach VTVM (HP 400H) to capacitor. Make connection at ground ring on the side opposite to that of oscillator connection to minimize the coupling of stray fields.

6.1.4 Raise oscillator voltage output to obtain several millivolts of capacitor voltage as measured on VTVM. Frequency of oscillator should be in range of 100 kHz. Vary oscillator frequency to obtain null on VTVM. The frequency which corresponds to the null in VTVM voltage is the capacitor resonant frequency. Record resonant frequency.

6.2 Calculate capacitor inductance using the following formula:

$$L = \frac{1}{C(2\pi f_o)^2}$$

7.0 Leak test

7.1 Leak test at 50°C ± 5°C (122°F ± 9°F) for two hours. Capacitor must be carefully wrapped in brown paper and be tested lying on side.

7.2 Vacuum leak test at 40°C ± 5°C (104°F ± 7°F) for minimum 0.5 hour at 0.1 Torr pressure or less. Use liner in dual impregnator.

8.0 Visually inspect all capacitors for poor workmanship and deviations from dimension limits.

Note: After sealing off at -20°C, it is possible that fill plug will protrude beyond welded edges of cover. This is normal and not a dimensional deviation.

B <u>Criteria for acceptance</u>.

1.0 Capacitance: 76.0 to 88 μF

2.0 Dissipation factor: 0.013 maximum at 2°C and 120 Hz

3.0 Ins. resistance: not specified. Uniformity of value should be within $\bar{X}$ ± 10 percent.

4.0 Inductance: 0.015 μH maximum

5.0 Hipot: No intermittent arc - over, no short circuit or open circuit. Leakage current after charge should not exceed 0.2 mA.

6.0 Dissipation factor must not <u>increase</u> more than 0.002 after hipot.

7.0 Equivalent series inductance shall not exceed 0.015 μH.

8.0 There shall be no oil leaks after either of two leak tests.

9.0 Capacitors shall be identified in a permanent manner, but shall not be labeled.

10.0 Capacitor shall meet dimensions of Drawing Number 72436.

APPENDIX B

HIGH ENERGY DENSITY CAPACITOR MEETING
APRIL 29, 1981
LIST OF ATTENDEES

HIGH ENERGY DENSITY CAPACITORS MEETING
APRIL 29, 1981
LIST OF ATTENDEES

Bill Bailey	Maxwell Laboratories, Inc. 8835 Balboa Avenue San Diego, CA 92123 (619) 279-5100
Michael R. Brasher	AFRPL/LKDH, Stop 24 Edwards AFB, CA 93523 (805) 277-5435
Martin Broadhurst	National Burearu of Standards Washington, DC 20234 (301) 921-3851
Dick Ferren	Pennwalt 900 First Avenue King of Prussia, PA 19406
Irv Galperin	Maxwell Laboratories, Inc.
G. H Mauldin	Division 2153, Sandia Labs P.O. Box 5800 Albuquerque, NM 87185 (505) 844-4260
Allen Ramrus	Maxwell Laboratories, Inc.
Gerald Rohwein	Sandia National Laboratories Box 5800, KAFB Albuquerque, NM 87185
Jim Sarjeant	Los Alamos National Laboratories E-11, MS429 P.O. Box 1663 Los Alamos, NM 87545 (505) 667-6832
Bob Vondra	AFRPL/LKDH, Stop 24 Edwards AFB, CA 93523 (505) 227-5540
Wayne White	Maxwell Laboratories, Inc.
Shiao-Ping S. Yen	JPL, Section 346, 122-123 4800 Oak Graove Dr. Pasadena, CA 91109 (213) 354-3105

APPENDIX C

CAPACITOR PRODUCT SPECIFICATION

Sheet ____ of ____

Specification No.	Chng. Ltr	Drawing No.	Eng.	Appr.	MAXWELL CAPACITOR PRODUCT SPECIFICATION
350203-25202		72436-1	CWW 3/15/82	CWW 3/15/82	

Catalog No.	Cap. μF	Tot. %	Volt (kV)	Dimensions	Winding	Assembly	Sub-Test	Impregnate	Paint	Qualification
34252	70	+15 -5	2.5	4.125 DIA x 6.25	EPS-3573	EPS-3513	EPS-3533	CASTOR OIL	NONE	

LIST OF MATERIALS					COST	LIST OF LABOR OPERATIONS			
Item No.	Stock No. Part No.	Description of Part	Qty. Per Assy.	Unit	Mat'l	Labor Oper.#	Description of Labor	No. of Oper's	Labor Hours
1.0	203-25202	WINDINGS	1	EA					
1.1		K E POLYMER 4 ROLLS 9 μm x 5.00	2.14	Lbs					
1.2	72435-1	PAPER 2 ROLLS .00025 x 5.00	.45	Lbs					
1.3	72433	FOIL 2 ROLLS .00023 x 4.81	1.03	Lbs					
1.4		CORE - ALUMINA TUBE 1.50 DIA x 5.00	1	EA					
2.0	METAL BELLOWS # 35099	BELLOWS	1	EA					
3.0	PER SKETCH	TUBE - 321 ST. STEEL 1.125 OD w/.020 WALL x 4.3	1	EA					
4.0	PER SKETCH	END CAPS 1.06 DIA x .025 ST STEEL	2	EA					
5.0		PLUG - POLYPROP 1.2 DIA x .50	1	EA					
6.0	23-00384	SOLDER J-22	.1	Lbs					
7.0	23-00435	SOLDER 60/40	.2	Lbs					
8.0	M/F 18-00226	TAB - TOP .005 x .25 x 1.45	6	EA					
9.0	72486	ELECTRODE	1	EA					
10.0	65430-3	TAB - ELECTRODE	1	EA					
11.0	85-01201	SCREW BRASS 8-32 x .25	1	EA					

Sheet ____ of ____

Specification No.	Chng. Ltr	Drawing No.	Eng.	Appr.
350203-25202				

MAXWELL CAPACITOR PRODUCT SPECIFICATION

Catalog No.	Cap. µF	Tot. %	Volt (kV)	Dimensions	Winding	Assembly	Sub-Test	Impregnate	Paint	Qualification
34252		+ -								

LIST OF MATERIALS					COST	LIST OF LABOR OPERATIONS			
Item No.	Stock No. Part No.	Description of Part	Qty. Per Assy.	Unit	Mat'l	Labor Oper. #	Description of Labor	No. of Oper's	Labor Hours
12.0	85-01074	WASHER	1	EA					
13.0	49-50116-017	INSULATOR ELECTRODE KAPTON	1	EA					
14.0	15-50110	INSULATOR - CAP	2	EA					
15.0	67-00280	TAPE - KAPTON	A/R						
16.0	17-00358	POLYPROPYLENE WRAP	A/R						
17.0	72436	CAN FAIRCHILD REPUBLIC	1	EA					
18.0	M/F 18-00226	TAB BOTTOM .005 x .25 x 3.0	6	EA					
19.0	49-50116	DISC - KAPTON 3.875 DIA x .005	1	EA					
20.0	72436	COVER BOTTOM FAIRCHILD REPUBLIC	1	EA					
21.0	12-00224	CASTOR OIL	.8	Lbs					
22.0	72436	PLUG - FILL HOLE	1	EA					

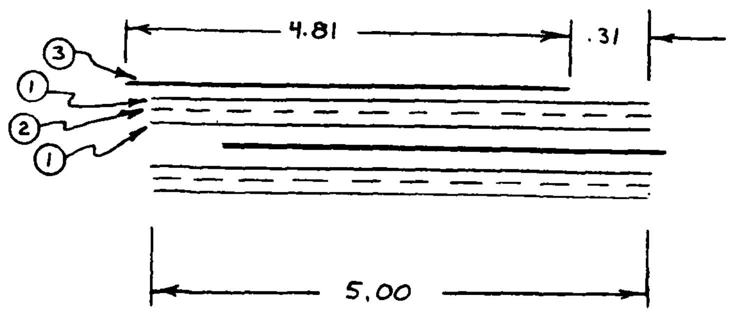
MAXWELL

CAPACITOR PRODUCT SPECIFICATION

Specification No.	Chng. Ltr	Winding Spec.#	Eng.	Appr.
350203-25202				CWW 3/15/82

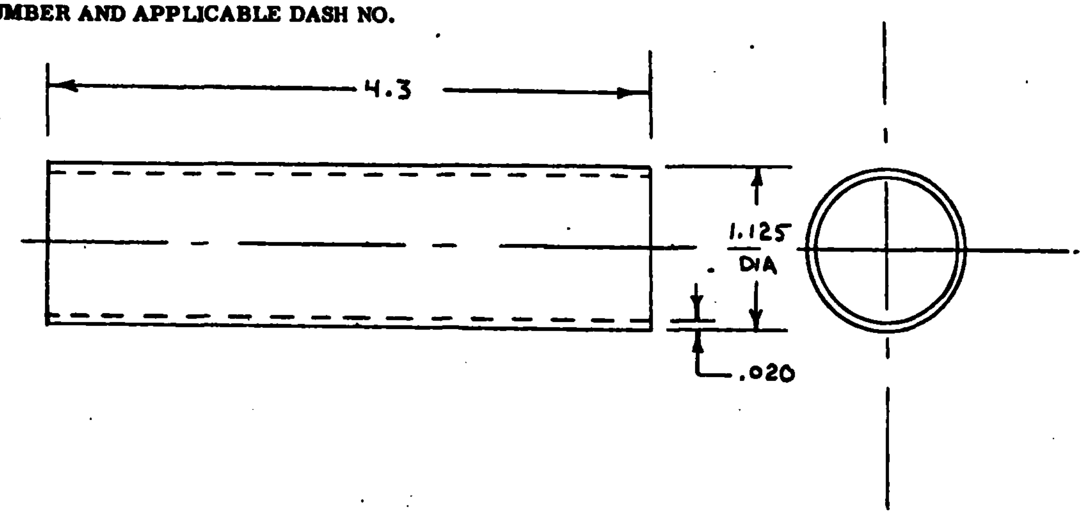
Arbor	DlyStrt	Foil Trn/Lgth.	DlyFin	Roll Dia.	DryCap	Dry DF	DCTest	E. F.	E. M.	I. M.	A. W.	# Sec/Wndg	Tolerance
1.5 CORE	15/9"	340 FT	24"	3.95 ±.05	40 µf	.03	2 KV	.12	.31	--	4.38	1	±.1 ±.03 ±.010

LIST OF MATERIALS					Per Winding				
Item No.	Stock No. Part No.	Description of Part	Qty. Per Assy.		Wound Length	Lb./ Winding	Remarks		
1.0		K F POLYMER 9 µm x 5.00	4	ROLLS	338 FT	2.14			
2.0	72435-1	PAPER .00025 x 5.00	2	ROLLS	338 FT	.45			
3.0	72433	FOIL .00023 x 4.81	2	ROLLS	335 FT	1.03			
4.0		CORE CERAMIC 1.50 x 5.00	1	EA					



CASTOR OIL

NOTES:
1. INTERPRET DRAWING PER MIL-STD 100.
2. REMOVE ALL BURRS AND SHARP EDGES UNLESS OTHERWISE NOTED.
3. MARK BY WITH THIS DRAWING NUMBER AND APPLICABLE DASH NO.



REVISION			
LTR	DESCRIPTION	DATE	APPROVED

PARTS LIST

QUANTITY REQD PER DASH NO.	CODE IDENT	ITEM NO.	PART NUMBER OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	STOCK SIZE	MATERIAL
					1 1/8 DIA x 4 5/16 TUBE	321 ST. STEEL

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES: FRACTIONS: ±1/16
.X ± .1 .XX ± .03 .XXX ± .010
HOLE DIA UP TO .500 +.005 −.002
ANGLES ±0°30' MACHINED SURFACES √

PROJECT MANAGER
PROJECT ENGINEER
APPROVED
CHECKED BY
DRAWN BY

CONTRACT NUMBER
DATE
PREPARED
CHECKED
ENGINEER
DESIGN ACTIVITY APPROVAL
GOVERNMENT ACTIVITY APPROVAL

NEXT ASSY	USED ON
350203-25202	

APPLICATION

MAXWELL

MAXWELL LABORATORIES, INC.
9244 BALBOA AVENUE
SAN DIEGO, CALIFORNIA 92123

TITLE: TUBE - STAINLESS STEEL

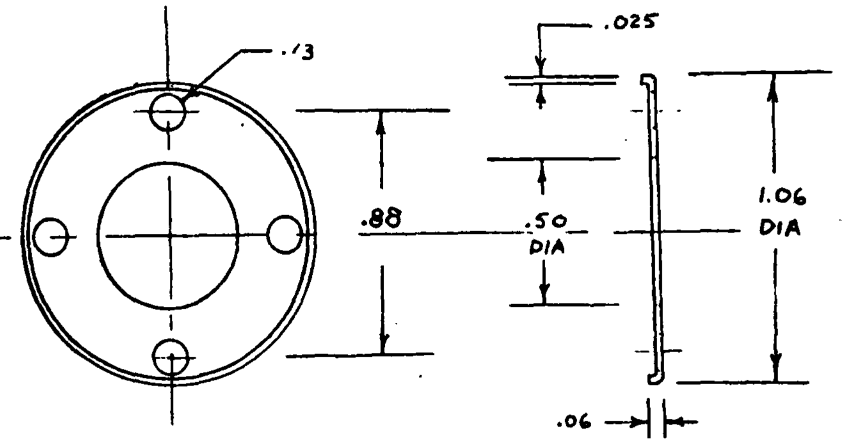
SIZE	CODE IDENT NO.	DRAWING NUMBER	REV
A	29813		

SCALE RELEASE DATE SHEET OF

9-80 ML-4

NOTES:
1. INTERPRET DRAWING PER MIL-STD 100.
2. REMOVE ALL BURRS AND SHARP EDGES UNLESS OTHERWISE NOTED.
3. MARK BY WITH THIS DRAWING NUMBER AND APPLICABLE DASH NO.

REVISION			
LTR	DESCRIPTION	DATE	APPROVED



								1 1/8 DIA x 24 ga	STAINLESS STEEL
				CODE IDENT	ITEM NO.	PART NUMBER OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	STOCK SIZE	MATERIAL
QUANTITY REQD PER DASH NO.				PARTS LIST					

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES: FRACTIONS: ±1/16
.X ± .1 .XX ± .03 .XXX ± .010
HOLE DIA UP TO .500 +.005 −.002
ANGLES ±0°30' MACHINED SURFACES √

PROJECT MANAGER	
PROJECT ENGINEER	
APPROVED	
CHECKED BY	
DRAWN BY	

CONTRACT NUMBER	
DATE	
PREPARED	
CHECKED	
ENGINEER	
DESIGN ACTIVITY APPROVAL	
GOVERNMENT ACTIVITY APPROVAL	

NEXT ASSY	USED ON
350203-25202	

APPLICATION

MAXWELL

MAXWELL LABORATORIES, INC.
9244 BALBOA AVENUE
SAN DIEGO, CALIFORNIA 92123

TITLE
END CAP - BELLOWS

SIZE	CODE IDENT NO.	DRAWING NUMBER	REV
A	29813		

SCALE	RELEASE DATE	SHEET	OF

FIL